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HORTICULTURAL PLANT CULTIVATION AND BREEDING

EDITOR

Doç. Dr. Hatice Filiz BOYACI

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CONTENTS

CHAPTER 1

SEED COATING TECHNIQUES

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1. INTRODUCTION

Global population growth and climate change necessitate new approaches to ensure productivity and sustainability in agricultural systems. Current data indicate that the world population, currently at 8 billion, is projected to reach 10 billion by 2050 and surpass 11.2 billion by the end of the century (Cardarelli et al., 2022). This demographic expansion poses unprecedented challenges to agricultural systems and further highlights the critical role of seed quality in determining crop productivity and sustainability (Javed et al., 2022).

The fundamental dilemma faced by modern agriculture lies in meeting the increasing food demand while maintaining ecological balance. Traditional intensive farming practices have led to several adverse outcomes, including soil fertility decline, water pollution, and loss of biodiversity. In particular, the uncontrolled use of chemical inputs may cause long-term effects on human health (Rahman and Zhang, 2018) and contribute to environmental degradation.

Seed coating applications were first inspired by the pharmaceutical industry and initiated in cereal crops in the 1930s, later becoming commercially widespread in the 1960s (Kaufman, 1991). Today, seed coating technologies are widely used in both horticultural and field crops worldwide and have gained a significant position in the global market (Pedrini et al., 2017). In this context, seed coating technologies offer an important solution for sustainable agriculture.

Sustainable development is based on the principle of meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (Pirzada et al., 2020). Supporting this principle, seed coating technology can:

1.Increase germination rates and seedling vigor (Lee et al., 2023)
2.Enhance tolerance to biotic and abiotic stresses
3. Support environmental sustainability by reducing chemical input use (Rahman et al., 2024)
4.Enable targeted delivery of nutrients (Kavusi et al., 2023)

Especially under irregular rainfall patterns and increasing stress conditions caused by climate change, seed coating applications can play a crucial role in ensuring stable crop performance. When integrated with precision agriculture practices, this technology can significantly improve resource use efficiency and contribute to the development of sustainable food production systems.

Seed coating can include the application of dyes and tracers (e.g., fluorescent dyes), protectants (e.g., pesticides), soil amendments (e.g., hydrophilic materials, water retainers), compounds enhancing germination, growth, and stress tolerance (e.g., salicylic acid, gibberellic acid, abscisic acid), macro- and micronutrients, and microbial inoculants (Ehsanfar and Modarres-Sanavy, 2005; Pedrini et al., 2017).

By applying beneficial substances as a protective layer on the seed surface, seed coating improves the microenvironment surrounding the seed and provides protection against various diseases (Javed et al., 2022). The main types of seed coating include film coating, pelleting, seed encapsulation, and plant-beneficial microbial (PBM) inoculation. The choice of method depends on the purpose of application, seed type, and selected microorganisms.

2. TYPES OF SEED COATING

a. Film Coating

Film coating is an innovative technique involving the application of functional materials in thin layers onto the seed surface, resulting in up to 5% increase in seed weight. In this method, active compounds are typically dissolved or dispersed in liquid carriers and then evenly applied onto seeds using fluidized bed systems or pharmaceutical coating drums. The resulting thin layer—composed of polymers, plasticizers, pigments, and solvents—covers the seed surface without significantly altering its size or shape.

This layer enhances seed handling properties, minimizes or eliminates the dusting of coating materials (e.g., pesticides, biological agents, or micronutrients), and improves application efficiency. Studies have reported that the film coating method can achieve material recovery efficiencies exceeding 90% (Pedrini et al., 2017). Recently, this technology has gained wide acceptance in the seed industry as a reliable and effective approach to improve the productivity of several major crops such as *Brassica napus*, *Glycine max*, *Gossypium sp.*, *Helianthus annuus*, *Medicago sativa*, *Triticum aestivum*, and *Zea mays* (Taylor et al., 2001; Accinelli et al., 2016; Oliveira et al., 2016; Zhou et al., 2017).

Protective Effects Against Stress Conditions

Biotic and abiotic stress factors encountered after sowing highlight the significance of film coating applications. Studies have demonstrated that coatings exhibit protective effects during the critical period from imbibition to seedling establishment:

- **Waterlogging stress:** In *Brassica napus L.* (canola) seeds, uniconazole-based film coating significantly enhanced the activities of antioxidant enzymes (peroxidase, catalase, and superoxide dismutase) and improved morphological parameters (Qiu et al., 2005).
- **Low temperature and humidity stress:** Polymer-based film coatings improved the germination performance of canola seeds under adverse environmental conditions (Willenborg et al., 2005).
- **Drought stress:** Coatings containing *Paraburkholderia phytofirmans* rhizobacteria enhanced drought tolerance in wheat seeds (Naveed et al., 2014). Similarly, microbial inoculant coatings were found to be effective in cowpea (*Vigna unguiculata L.*) under water scarcity (Rocha et al., 2019).

Effects on Physical and Biological Properties

Film coating technology enhances seed quality on multiple levels:

- **Sowing quality:** In maize, polymer coatings reduced sowing errors (skips or doubles), improving operational efficiency by 15–20% (Avelar et al., 2012).
- **Biotic stress management:** *Lepidium sativum* and sugar beet seeds coated with *Pythium oligandrum* oospores achieved 40–60% protection against damping-off disease (McQuilken et al., 1994).
- **Physiological activity:** In pigeon pea seeds coated with zinc and iron nanoparticles (750 ppm), dehydrogenase and amylase activities increased by 2–3 fold (Accinelli et al., 2016).

Technological Limitations and Optimization

Several critical aspects must be considered in film coating applications:

- **Gas exchange balance:** Polyvinyl-based coatings have been reported to restrict oxygen diffusion in sugar beet, reducing germination by 15–20% (Duan and Burris, 1997).
- **Material selection:** Chitosan and PEG-based coatings increased the germination rate of castor bean by 30%, whereas some synthetic polymers showed adverse effects (Chandrika et al., 2019).

b. Seed Pelleting

Seed pelleting is defined as the process of increasing seed size by coating it with inorganic or organic additives to a degree that masks its original morphology (Pedrini et al., 2017). This technique plays a crucial role in improving the mechanical sowing suitability of small-sized seeds.

Studies on various crop species have demonstrated the positive effects of pelleting on agronomic parameters. For instance, pelleting of tomato (*Solanum lycopersicum L.*) seeds resulted in a 15–20% increase in germination rates and significant improvements in seedling vigor indices (Afzal et al., 2020). Seed pelleting using combinations of talc, calcium oxide, and bentonite substantially enhanced compatibility with sowing machines.

In soybean (*Glycine max L.*), pellet formulations containing ammonium molybdate, ferrous sulfate, and *Rhizobium*inoculum increased plant height and seed yield by up to 25%. Similarly, in vegetable cowpea (*Vigna unguiculata L.*), pelleting with micronutrients and plant extracts markedly promoted vegetative growth (Masuthi et al., 2009).

In sesame (*Sesamum indicum L.*), pelleting with plant growth-promoting rhizobacteria (PGPR, strain E681) reduced damping-off (*Pythium spp.*) incidence by 40–60%, enhanced biological control efficiency, and improved seedling emergence. In rice (*Oryza sativa L.*) grown under flooded conditions, calcium peroxide-based pelleting facilitated oxygen diffusion and increased germination rates by 30%.

Storage studies revealed that physiological aging indices in pelleted cowpea seeds were 15% lower compared to untreated seeds. According to Pedrini et al. (2017), the pelleting technique requires 3–5 times more coating material and 2–3 times longer processing duration than film coating and encrusting methods.

c. Seed Encapsulation

Seed encapsulation has emerged as an increasingly important technology in modern agriculture. This method increases seed weight by 8–500% while maintaining the original seed shape (Pedrini et al., 2017). The process generally consists of two stages: pre-coating preparation (BC) and coating process (CP). During the preparation stage, the initial properties of the seed are recorded, followed by gradual application of powders and binders onto the seed surface during coating (Pedrini et al., 2018).

Research has demonstrated notable improvements in encapsulated seeds. For example, radicle development increased by up to 25%, while in sunflower, the adverse effects of herbicides were reduced by 40% (Szemruch and Ferrari, 2013). In basil seeds, pre-storage encapsulation increased germination rates by 35% and improved vigor index by 1.8-fold (Olivera et al., 2017).

From a formulation standpoint, although weight gain in cabbage seeds decreased germination by 15%, soy flour supplementation doubled granule strength and shortened dissolution time by 30% (Wu et al., 2018; Qiu et al., 2020). Incorporation of beneficial microorganisms such as PGPR increased microbial survival rates by 60% during storage and extended shelf life by 3–5 weeks (Ma, 2019).

For example, encapsulation of onion seeds with a Thiram:Genus's Coat (1:1.2) formulation increased root length by 40% and improved vigor index by 2.1-fold (Patil et al., 2019). Environmentally, this technology can reduce soil contamination by 55% and limit negative effects on non-target organisms by 70% (Pedrini et al., 2017).

While the 60% increase in microbial survival represents a major advantage, the 15% reduction in germination due to weight increase constitutes a limitation. Economically, although shelf life can be extended by five weeks, the associated 25–30% cost increase is a factor that cannot be ignored.

d. Microbial Inoculation (PBM)

Seed inoculation is considered a precise and cost-effective method for the delivery of microbial inoculants (Ehsanfar and Modarres-Sanavy, 2005) and possesses strong potential for large-scale application. PBM seed coating involves the application of an active ingredient (e.g., microbial inoculant) to the seed surface using a binder, sometimes with filler materials serving as carriers.

Seed coating is regarded as a promising approach for inoculating different plant seeds, as it allows precise application of small quantities of inoculum (Rouphael et al., 2017; Scott, 1989). Consequently, PBMs become readily available to plants during germination and early growth stages, promoting healthy and rapid seedling establishment and maximizing crop yield (Colla et al., 2015a).

Plant-beneficial microbes (PBMs) encompass various microorganisms that promote plant growth through direct and indirect mechanisms. These include bacteria and fungi that contribute to nutrient acquisition, disease suppression, and stress tolerance. The use of PBMs in agriculture has increased significantly, as these microorganisms provide multiple benefits such as biofertilization, phytostimulation, and biocontrol (Kavusi et al., 2023). Table 1 summarizes the effects of different nutrient-based seed coatings on seed quality and crop performance.

Table 1. Seed coating applications with various sources and their findings

Source	Application Method	Application Dose	Crop	Findings	References
Boron	Seed Coating	1.5 g B/kg	Chickpea	Seedling growth, nodulation, and grain yield increased	(Hussain et al., 2020)
$ZnSO_4$	Seed Coating	8.81 g $ZnSO_4 \cdot 7H_2O$/kg seed	Rice	Activities of sulfur metabolism enzymes increased	(Da-Costa et al., 2020)
Calcium Peroxide	Seed Coating	6 g/20 g seed	Rice	Emergence, physio-morphological, and biochemical traits significantly improved	(Javed et al., 2021)
Zinc	Seed Coating	1.5 g Zn/kg	Wheat	Germination improved	(Mohammad & Pekşen, 2020)

3. SEED COATING MATERIALS

The selection of coating materials significantly influences seed performance. The primary objective of seed coating materials is to enhance seed health and quality while creating a favorable microenvironment for beneficial microorganisms. Accordingly, coating materials can be categorized as inorganic, organic, polymeric, biological agents, and supplementary additives.

a. Inorganic Materials

Among the most commonly used inorganic materials are lime, gypsum, montmorillonite, kaolinite, rock phosphate, and bentonite. These substances improve the structural integrity and water-holding capacity of the coating. Moreover, materials such as vermiculite (Cho et al., 2000) and dolomite (Nasatto et al., 2015) have also been used as alternative additives in seed coating formulations. Their mineral composition contributes to enhanced aeration, mechanical stability, and water retention, which are crucial during germination and early seedling growth.

b. Organic Materials

Organic-based materials contribute to seed development through their nutrient composition and biological activity. For instance, moringa leaf powder is rich in calcium, potassium, phenolic compounds, ascorbates, antioxidant proteins, and cytokinins (zeatin), thereby improving seed quality (Makkar et al., 2007). The use of moringa leaf extract has been shown to increase shoot and root biomass as well as fruit number in cabbage and rape plants (Culver et al., 2012).

Other organic coating materials include peat, poultry manure, farmyard manure, plant mucilage, and bone meal (Delin et al., 2018). These organic sources not only provide essential macro and micronutrients but also improve soil microbial activity and structure after seedling establishment.

c. Polymers

Polymers play a key role in enhancing both adhesion during coating and the controlled release of bioactive compounds. These materials aid in targeted nutrient and protectant delivery to the seed. Particularly, water-retaining polymers maintain moisture balance around the seed, thereby promoting early germination and root development. Polymers such as polyvinyl alcohol (PVA), polyethylene glycol (PEG), and carboxymethyl cellulose (CMC) are widely used due to their biocompatibility and ability to form thin, stable films that modulate gas and water exchange.

d. Biological Agents

Beneficial microorganisms integrated into coating materials promote seedling growth and strengthen plant defenses against soil-borne pathogens. Bacterial species such as *Rhizobium* fix atmospheric nitrogen, while certain fungi enhance phosphorus solubility, thus contributing to plant nutrition. These bio-based coatings also reduce the need for synthetic fertilizers, supporting sustainable agricultural practices (Backer et al., 2018; Kavusi et al., 2023). The inclusion of *Bacillus*, *Pseudomonas*, and *Trichoderma* strains is particularly effective in enhancing seedling vigor and disease resistance.

e. Nutrient Elements

The use of macro and micronutrients essential for early growth is common in seed coating formulations. Elements such as zinc and boron have been reported to improve plant vigor and stress resistance (Dhaliwal et al., 2022). For example, zinc functions as a cofactor in auxin synthesis and enzyme activation, while boron is essential for cell wall stability and reproductive development. Controlled-release nutrient coatings can provide a steady nutrient supply during early seedling growth, reducing the need for frequent fertilizer applications.

f. Adhesive Agents

To ensure proper adhesion of coating materials to the seed surface, binders such as gum arabic or cellulose-based polymers are employed. These agents enhance coating stability and prevent fragmentation during storage and handling. Moreover, binder selection affects the release rate of nutrients and active compounds, thereby determining their bioavailability to the plant (Patyal et al., 2025). For instance, natural adhesives like starch and gelatin tend to support microbial viability, whereas synthetic adhesives may offer better mechanical strength but lower biological compatibility.

4. SEED COATING EQUIPMENT AND PROCESS

The equipment used in the seed coating process must ensure the physical integrity of the seeds while allowing a uniform and controlled deposition of coating materials on their surface (Afzal et al., 2020). The quality of coating is directly influenced by several factors, including the width and rotation speed of the equipment, particle fineness of the coating material, porosity, and water-holding capacity (Gorim and Asch, 2012). In addition, maintaining a consistent seed movement within the coating pan facilitates effective adhesion of both binder and powder materials to the seed surface (Afzal et al., 2020).

To achieve these goals, various coating systems have been developed. The most commonly used device is the rotating pan, in which seeds are slowly tumbled within an inclined drum while coating materials are applied. After coating, sieving and drying steps are performed (Halmer, 2000; Pedrini et al., 2017).

A more advanced system, the fluidized or spouted bed, keeps seeds suspended in an upward stream of warm air while the coating solution is sprayed onto them. This method allows precise and uniform coating but is relatively slower and more expensive compared to traditional pan coating (Robani, 1994).

Similarly, the rotary coater (rotor–stator system) uses two rotating discs inside a cylindrical chamber to atomize and spray the coating formulation evenly over the seed mass (Pedrini et al., 2017). This technique offers high precision and control over coating thickness and material distribution, making it suitable for industrial-scale applications.

Beyond these standard approaches, methods originally developed for other industries have been adapted to seed coating. For example, pharmaceutical tablet coating technologies (Sauer et al., 2013) and pesticide fungicide spraying systems (El-Mohamedy and Abd El-Baky, 2008) have been successfully modified for agricultural use.

In large scale operations, mixers with large, inclined drums similar to those used in the cement industry have been found to be suitable for seed coating due to their high load capacity and efficient blending action. However, the scientific literature provides limited information on the technical specifications of such equipment, as most commercial applications are conducted by private seed technology companies (Ugoji et al., 2006; Diniz et al., 2009; Junges et al., 2013; Rozier et al., 2017).

Overall, the optimization of coating parameters including seed flow dynamics, binder viscosity, and drying conditions is essential for achieving high coating uniformity, minimizing dust formation, and maintaining seed viability during processing and storage.

5. MICROBIAL INOCULATION SYSTEMS

Microbial seed coating technology plays a critical role in establishing symbiotic relationships, particularly in leguminous crops. Studies by Sogut (2006) and Mia et al. (2012) have shown that rhizobial inoculation can increase root nodulation by 60–80% and significantly promote plant growth in legumes. The success of this system depends on three major factors:

a) Selection of Microbial Strain

Küçük and Kıvanç (2008) emphasized that different *Rhizobium* species (e.g., *Bradyrhizobium japonicum*, *Rhizobium leguminosarum*) must be specifically matched to their host plants. Incorrect strain selection may prevent the establishment of symbiosis, leading to reduced nitrogen fixation and yield loss. The host specificity of rhizobia is therefore a critical determinant for the efficiency of microbial inoculation systems.

b) Carrier Matrix

Tufail et al. (2018) demonstrated that carbon-based carriers such as maltodextrin and carboxymethyl cellulose (CMC) not only provide a nutritional source for microorganisms but also form a protective barrier that enhances microbial survival. These carriers protect inoculated microbes from environmental stress factors such as UV radiation and temperature fluctuations, ensuring their viability until seed germination and root colonization.

c) Application Technique

Glodowska et al. (2017) reported that peat and biochar serve as ideal carriers for microbial inoculants, maintaining viable *Rhizobium* populations for up to six months. These substrates create a porous and stable microenvironment that supports microbial respiration and moisture retention. However, excessive drying of inoculated seeds can reduce microbial viability by up to 90%, highlighting the need for optimized drying protocols following inoculation.

Overall, the success of microbial inoculation systems depends on achieving a balance between microbial survival, coating stability, and compatibility with seed physiology. Properly formulated microbial coatings not only enhance early nodulation and nutrient uptake but also contribute to sustainable crop production by reducing dependency on synthetic nitrogen fertilizers.

6. COMPARATIVE ANALYSIS OF CHEMICAL AND BIOLOGICAL PROTECTIVE SYSTEMS

Under acidic soil conditions ($pH < 5.5$), the lime–rhizobium combination becomes particularly important. Bambara and Ndakidemi (2010) demonstrated that the optimal $CaCO_3$/rhizobium ratio is 3:1 (w/w), which mitigates acidic stress while maintaining microbial viability. Padhi and Pattanayak (2018) further reported that this system could increase yield by 2.1-fold even in soils with pH 4.8.
Regarding the efficacy of fungicide coatings, Lamichhane et al. (2017) reported 85% inhibition against *Pythium ultimum*, while Pan et al. (2006) observed that acaricide coatings reduced *Tetranychus urticae* populations by 80%.

7. EFFECTS OF NUTRIENT-ENRICHED COATING SYSTEMS ON PLANT PHYSIOLOGY

Controlled release of nutrient elements optimizes plant growth, particularly during early vegetative stages:
a) **Zinc Coating:** Mohammad and Pekşen (2020) reported a 28% increase in germination rate and accelerated root development in wheat seeds coated with $ZnSO_4 \cdot 7H_2O$. Zinc acts as a cofactor in auxin synthesis.
b) **Phosphorus Coating:** Peltonen-Sainio et al. (2006) observed a 2.3-fold increase in early root biomass in barley seeds coated with $Ca(H_2PO_4)_2$. Phosphorus plays a critical role in early-stage energy metabolism.
c) **Sulfur Coating:** Balasubramanian and Hill (2002) reported a 75% increase in nodulation in alfalfa seeds coated with elemental sulfur. Sulfur is essential for amino acid synthesis, particularly in legumes.

8. EFFECTS OF POLYMERIC MATRICES ON WATER DYNAMICS

Significant findings have been reported regarding the water-holding capacity of hydrogel polymers such as polyvinyl alcohol (PVA) and carboxymethyl cellulose (CMC). These polymers stabilize the relative humidity (RH) of the microenvironment within 40–60%, reduce radicle emergence time by 12–18 hours, and increase root biomass by 25%. They enhance water-use efficiency, especially in arid and semi-arid regions.

9. COMPARISON OF ADHESIVE SYSTEM PERFORMANCE

The choice of binder directly influences the success of seed coatings. Comparative studies by Fasina (2008) and Patyal et al. (2025) reported: Arabic Gum: low-cost (2.5–3.5 USD/kg) but maintains limited microbial viability (30–40%); Soy Protein: medium-cost (4.0–5.0 USD/kg) and maintains good microbial viability (75–85%); Polyvinyl Alcohol (PVA): high-cost (6.0–7.5 USD/kg) but exhibits very high water solubility (95–98%).

10. ADVANTAGES OF MULTI-LAYERED COATING SYSTEMS

Recent technological developments highlight the benefits of multi-layered coating systems: Inner Layer – microbial inoculant + peat matrix (viability up to 180 days); Middle Layer – lime buffer + nutrient elements (pH stabilization); Outer Layer – polymeric barrier + controlled-release fungicide (8–10 weeks of protection). These systems provide multiple functions simultaneously in a single application.

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CHAPTER 2

NANOTECHNOLOGY APPLICATIONS IN VITICULTURE: INNOVATIVE APPROACHES FROM THE PERSPECTIVE OF YIELD, QUALITY, AND SUSTAINABILITY

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1. INTRODUCTION

Viticulture is one of the most value-added sectors of agriculture, but it has recently been facing increasing structural problems due to climate change, high production costs and higher quality standards. Irregular climate patterns, including heat stress, unpredictable rainfall, and proliferation of pests, have a direct negative effect on both quantity and quality of grapes. At the same time, changing consumer preference for organic and residue free products along with competition from global markets, force the producers to follow production techniques, which are economically viable, sustainable and quality based (Fraceto et al., 2016).

In this context, nanotechnology has become a prominent facilitator for the three key pillars of wine growing: yield, quality, and sustainability. Nano-fertilizers and nano-pesticides promote uptake of nutrients, boost physiological tolerance of plants, and allow high precision of pest-control (Khot et al., 2012; Chhipa, 2017). In addition, such nano-formulations frequently also result in lower production costs, less chemical residues and less environmental damage (Kah et al., 2018).

In terms of quality improvement, nano-encapsulation and smart carrier systems have been successfully applied for enhancement of phenolic composition, aroma profile and postharvest shelf life. For example, controlled hormone release with metal oxide nanoparticles (especially ZnO and SiO_2) has been recognized to directly affect berry development and its biochemical properties (Nair et al., 2010).

Nanobiotechnological strategies have been effective for enhancing vine tolerance to drought, salinity, and temperature stress in the realm of climate adaptation. Mesoporous silica nanoparticles, which can deliver genetic materials or bioactive molecules into plant cells, are considered a revolutionary new tool in this field (Torney et al., 2007). Moreover, with nano-sensor technology, key physiological parameters (water potential, stress proteins, photosynthetic activity, among others) that directly affect plant health can be monitored in real-time for more intelligent, data-based irrigation and fertilization management (Parameswari et al., 2024; Yasir et al., 2025).

Taken together these developments firmly establish that nanotechnology in viticulture is not merely an emerging trend but an essential criterion for the sustainable, quality and quantity production. The next section provides a detailed overview of its present applications, working principles, risks, and possible future trends in the field of viticulture.

2. FUNDAMENTAL PRINCIPLES AND MECHANISMS OF NANOTECHNOLOGY IN VITICULTURE

Nanotechnology is the technology of the future and is currently related to the production and application of materials, devices, and systems by controlling matter at the scale of 1–100 nm, resulting in novel properties and functions. At this scale, the material has a high surface area, ion exchange capacity, and biological activity, which allow for superior performance in agricultural systems. The essential concepts of nanoagriculture are controlled release, target action and biocompatibility, increased efficiency and environmental-friendly (Singh et al., 2025). In viticulture, where the enterprise is as sensitive to climatic stress and the balance between yield and quality is delicate, these characteristics can be customized for use at each stage of the production chain.

2.1. Mechanism and Applications of Nano-Fertilizers

Nano-fertilizers are processed forms of traditional fertilizers of submicron scale dimensions. Ion exchange at the root surface and leaf interface is also easier in this structure, because of which ion uptake and translocation are enhanced (Abdalla et al., 2022). When interacting with water, nanoparticles have special solubility and surface tension characteristics that result in a controlled release mechanism. In viticulture, nanoparticles, including ZnO, Fe_2O_3, CuO, and SiO_2, are potent in the stimulation of chlorophyll synthesis, enzymatic activity, and antioxidant defense system (Kilic et al., 2025; Zhang et al., 2024).

Kour et al. (2025) showed that nano-nitrogen and nano-iron combination enhanced leaf greenness (SPAD values) and photosynthetic performance in grapevines by 18–25%. Further, Singh and Kalia (2019) revealed that nano-fertilizers contribute in sustaining microbial balance hence enhance the soil fertility in long-run, which is a crucial factor or sustainable management of vineyards.

The ability to increase drought tolerance through nano-fertilizers application is another important aspect. Treatment with nano-silicon and nano-iron maintains osmotic balance in the root and ensures maximum water use under dry conditions (Rai & Avila-Quezada, 2024). Thus, nanotechnology has a dual role for enhancing yield and an efficient means of adapting to climate change.

2.2. Nano-Pesticides and Plant Protection Mechanisms

Nano-pesticides are novel formulations or systems in which active pesticide ingredients are encapsulated or emulsified in nano-sized carriers. This arrangement makes it possible for lower doses to be more effective and longer acting via slow release mechanisms (Atanda et al., 2025). Nanoparticles contact insect cuticles/enzymatic systems and cause biochemical disorders and enhance the efficiency of the pesticides. This method effectively overcomes the problem of environmental residues associated with traditional pesticides (Kilic et al., 2025; Singh et al., 2025).

In grapevine, nanoformulations tested toward the fungal agents of powdery (*Uncinula necator*) and downy (*Plasmopara viticola*) mildews, have demonstrated the applicability of such solutions. CuO and ZnO nanoparticles act as fungicidal and antimicrobial agents, with the addition that silver (Ag) nanoparticles act as a broad spectrum agent (Zhang et al., 2024). Nano-pesticides enhance surface residue by 4–6 folds, leading to decreased frequency of application, reduced costs and lesser contamination of environment (Khan et al.

Lately, nano-biopesticides are receiving more attention as environmentally friendly alternatives. Organic polymer-based capsule systems allow for nanoformulation production of plant extracts or biologic materials. Atanda et al. (2025) raised that nano-biopesticides provide non-toxic eco-friendly solutions to pest control in vineyards.

2.3. Nano-Sensors and Smart Vineyard Management

Among the most innovative potentials of nanotechnology in winegrowing is the application of nano-sensors. They are able to measure parameters of the plant metabolism such as water status, nutrient status, stress proteins, and photosynthetic activity in real-time. In general, nanosensors are fabricated from materials such as carbon nanotubes (CNTs), silver nanowire networks, or gold nanoparticles-based electrode systems (Rai & Avila-Quezada, 2024). They are the basis for the “smart vineyard” principle.

Singh et al. (2025) highlighted that system based on nanosensor can monitor the moisture content of the soil and the temperature of the leaf and incorporate this information into automated irrigation management systems. These systems have been the critical factor in precision viticulture approach. In addition, improvement in food safety monitoring is achieved by nanosensors detecting pesticide residues and heavy metals accumulation (Zhang et al., 2024).

2.4. Nanobiotechnological Interactions and Cellular Mechanisms in Grapevines

The performance of nanotechnology is largely determined by its mechanisms of interaction with plant cells. Nanoparticles are transported via the apoplastic and symplastic routes at the root level and later access the xylem and phloem. Their behavior (mobility and reactivity) is influenced by surface charge, particle size, and chemical composition (Khan et al.,2025). Specially, ion-doped NPs (ionenriched formulations) modulate reactive oxygen species (ROS) homeostasis in plant metabolism, which positively correlates with stress tolerance.

Rai and Avila-Quezada (2024) observed an enhancement in phenolic and anthocyanin production in grape leaves under the influence of nano-CuO application, which indirectly leads to better fruit quality. Consistent with our study, Kour et al. (2025) reported that nano-nitrogen application enhanced the protein synthesis and aroma precursor metabolites content in grape. Taken together, these results demonstrate that nanotechnology improves the productivity and bio-chemical quality of grape production.

3. APPLICATIONS OF NANOTECHNOLOGY IN VITICULTURE

The methodologies employing nanotechnology in grape-growing have made astonishing progress during the last years, and today can be adopted at nearly all production stages need. Nano-fertilizers and nano-pesticides as encapsulating systems and nano-sensing are the available products that can increase production, quality, and contribute to reduce environmental damage. The main fields of application of these viticulture technologies and methods are described as follows.

3.1 Nano-Fertilizers and Plant Nutrition Management

Compared to traditional fertilizers, nano fertilizers are advantageous by releasing plant nutrition in controlled and targeted manner. And this enhances efficiency of nutrient utilization also reduces loss and leaching of nutrients from the soil (Abdalla et al., 2022). In viticulture, the use of nano-fertilizers is vital for the equalized supply of macro and micro-elements such as N, P, K, Zn, Fe, and Si.

In Fruit Research, Zhang et al. (2024) found that nano-iron (Fe_2O_3) and nano-zinc (ZnO) applications enhanced chlorophyll content and photosynthetic rate in grapevines by 15–25%, leading to higher yield and berry weight. Moreover, Kour et al. (2025) found very significant increase in shoot length, greenness of leaves (SPAD value) and berry diameter in nano-nitrogen fertilizers administered vineyards. Nano-fertilizers are likewise expected to sustain the biodiversity of soil microbes by reducing a nutrient imbalance. Nanoformulations promote the plant growth with saving the microbial activity and sustainable fertility of soil in long-run Singh, 2025. Up to 40% less material is needed when making nano-fertilizers compared to traditional fertilizers, making them an integral part of the simultaneously financial and environmental sustainability (Rai & Avila-Quezada, 2024).Applications of nano-silicon (SiO_2) have been shown to improve drought tolerance in grapevines by enhancing cuticular thickness on leaf surfaces, which reduces transpiration-induced water loss (Singh & Kalia, 2019). Such practices are regarded as essential adaptation tools for viticulture under the impacts of climate change.

3.2. Nano-Pesticides and Pest Management

Control of pests and diseases is essential to reduce yield losses in vineyards. However, the intensive application of traditional pesticides usually results in environmental toxicity and residue problems. To address these issues, nano-pesticides have been designed, based on the principles of nanotechnology where active ingredients are encapsulated or made into nano-emulsions (Atanda et al., 2025).

The nano-CuO and nano-ZnO particles showed high activity against the grapevine pathogens, *Plasmopara viticola* (downy mildew) and *Uncinula necator* (powdery mildew) reported by Khan et. (2025) The oxide nanoparticles attach to the pathogen cell wall and penetrate via ion release to inflict membrane damage and create oxidative stress. This mechanism provides a more sustained and targeted activity in comparison to conventional pesticides.

Zhang et al. (2024) reported that nano-pesticides extended the persistence on the leaf surface by 1–5 times, and the application frequency was reduced by 50%, which reduced the labor cost and the exposure of environmental pesticides. Recently, nano-biopesticides have been produced by incorporating natural active ingredients (such as plant extracts, microbial agents) into nanoemulsions. Neem extract at a concentration of 30% in nano-emulsion against the grape pest *Lobesia botrana* was found to offer 70% protection (Atanda et al., 2025). Such biologically derived nano-pesticides play a vital role in achieving residue-free production in viticulture.

Furthermore, the environmental effect of nano-pesticides is much weaker than that of traditional ones. Singh et al. (2025) proved that the photodegradation resistant structure of the nanoformulations leads active ingredient to loss less and results less accumulation of toxic residues in soil. This supports planetary health of both food safety and the ecosystem within vineyard systems.

3.3. Nano-Encapsulation Systems and Quality Management

Active compounds such as vitamins, antioxidants, aroma molecules, and growth regulators can be protected and released in a controlled manner by nanoscale carrier systems using the nanoencapsulation technique (Rai & Avila-Quezada, 2024). This approach plays a crucial role in preserving compounds that directly influence grape and wine quality.

For example, Nair et al. (2010) demonstrated up to 10% increase in berry size when gibberellic acid (GA_3) was applied through nano-encapsulation. Similarly, the phenolic compounds - nano-ZnO-encapsulated also exhibited higher antioxidant activity in grape leaves (Singh & Kalia, 2019).

Nano-encapsulation is also employed to minimize the loss of quality after harvest. Nano-cellulose and chitosan based coating films can effectively prolong the shelf life of grapes, resist microbial invasion and guard against oxidative degradation. In a report published in Fruit Research (Zhang et al., 2024) have demonstrated that nano-chitosan film coatings extended cold storage life of grapes from 21 to 35 days. These results indicate that nanotechnology could be successfully applied not only in production, but also in the postharvest quality preservation and supply chain management.

3.4. Nano-Sensors and Precision Viticulture

Nano-sensor technologies represent a key component of the “smart viticulture” concept. The sensors allow for monitoring, in real-time, the nutrient status of the plants, water stress, photosynthetic activity, and pest incidence (Singh et al., 2025). Rai and Avila-Quezada (2024) has also shown that nanosensor based on carbon nanotube (CNT) can monitor water loss and osmotic pressure in grape leaves and be incorporated with automated irrigation system to save water by 30%.

Furthermore, they detect pesticide residues, heavy metals etc. Khan et al. (2025) showed the AgNP based biosensors for detection of pesticide residues on grapes at the level of 0.1 ppm. Such technologies hold transformative potential for food safety monitoring.

Integrating nanosensors into vineyard management ensures transparency for both producers and consumers. Having the ability to track processes from soil to bottle using sensor data brings ‘smart vineyards’ in sight (Singh et al., 2025).

3.5. General Evaluation

Nano-fertilizers, nano-pesticides, nano-encapsulation systems, and nano-sensors are able to contribute for a full achievement of the yield, quality, and sustainability objectives in viticulture. These technologies are not only much cheaper to implement than traditional production, but also far less damaging to the environment. In conclusion, nanotechnology benefits viticulture via three core pathways:

1. Efficiency: Nutrient controlled release, pest management.
2. Quality: Improvements in phenolic composition, aroma and shelf life.
3. Sustainability: Diminishing use of resources and environmental toxicity.

The commercialization of these technologies may open the way to the worldwide spreading of "smart viticulture" and "green production" modes in the next decade.

4. EXPERIMENTAL FINDINGS AND LITERATURE REVIEW

Applications of nanotechnology in viticulture have been largely theoretical until now, with many laboratory and field trials proving their effectiveness and viability. This part brings experimental studies published between 2015 and 2024, where the comparative outcomes of nano-fertilizer, nano-pesticide, nano-encapsulation, and nano-sensor on production, quality, and environment parameters are presented.

4.1. Nano-Fertilizer Applications: Yield and Nutrient Uptake

The effects of nano-fertilizers on nutrient absorption, photosynthesis, and growth parameters of grapevines have already been described in several papers. Numerous studies were conducted on the impact of nano-fertilizer on the absorption of nutrients, photosynthetic efficiency, and growth variables of grapevines. Research by Cakmakci et al., (2022); Khot et al. (2012) and Singh et al. (2025) revealed that nanoformulations enhance ion transport during root absorption processes leading to yield improvements. The following table summarizes the typical enhancements achieved by various types of nano-fertilizer on grapevines performance.

Table 1. Effects of different nanoformulations on grapevine growth and physiological parameters

Nanoformulation	Target Parameter	Increase (%)	Source
Nano-ZnO	Leaf chlorophyll content (SPAD)	+22%	Zhang et al. (2024)
Nano-Fe_2O_3	Photosynthetic activity (Fv/Fm)	+18%	Singh et al. (2025)
Nano-SiO_2	Water-use efficiency	+25%	Rai & Avila-Quezada (2024)
Nano-NPK	Shoot length and berry size	+15–20%	Kour et al. (2025)
Nano-Mn/Zn mixture	Antioxidant activity and phenolic content	+28%	Singh & Kalia (2019)

The largest benefit of nano-fertilizers as compared to the traditional formulations is that they are more dose efficient. Nano-fertilizers can be used with 40% less input to produce the same yield, according to Abdalla et al. (2022). In addition their stability at different pH levels allows for increased uptake of micronutrients in calcareous soil (pH > 7.5), a soil type that is naturally found in vineyards.

Taken together, the above findings suggest that nano-fertilizers enhance yield, and appear to be a promising approach to increase nutrient use efficiency (NUE) and environment-friendly production.

4.2. Nano-Pesticides: Experimental Findings on Pest Control

Studies on nano-pesticides application in grapevine were mainly related to the pathogens *Plasmopara viticola* (downy mildew) and *Uncinula necator* (powdery mildew), which are responsible for 40–60% production loss in vineyards.

Khan et al. (2025) demonstrated that the foliar spray of CuO nanoparticles inhibited the development of downy mildew up to 70% and was active for a period of 15 days—40% higher than that of the conventional $Cu(OH)_2$ formulations at the equivalent concentration. Correspondingly, Zhang et al. (2024) found that ZnO nanoparticles significantly inhibited spore germination and exhibited a 4-fold longer duration on leaf surfaces when compared with the traditional pesticides, highlighting the significance of photodegradation resistance for nanoformulations.

Table 2. Effectiveness of different active nanoformulations in grapevine pest and disease management

Active Nanoformulation	Target Pathogen	Effectiveness (%)	Application Frequency (relative to conventi	Source
CuO nanoparticles	*Plasmopara viticola* (downy mildew)	70%	1/2	Khan et al. (2025)
ZnO nanoparticles	*Uncinula necator* (powdery mildew)	68%	1/3	Zhang et al. (2024)
Nano-SiO_2 + Neem extract	*Lobesia botrana* (grapevine moth)	72%	1/2	Atanda et al. (2025)
AgNP-based formulation	Bacterial pathogens (general)	85%	1/3	Singh et al. (2025)

Widely available biopesticides based on plant and microbe ingredient materials, nano-biopesticides are no exception, even exhibiting superior functionality. Atanda et al. (2025) showed that nanoemulsions with neem extract were 72% efficacious against *Lobesia botrana*, unlike 45% for the conventional extract.

These results suggest that nano-pesticides can effectively manage pests and provide sustainable management with reduced frequency of application.

4.3. Nano-Encapsulation Systems: H Quality Attributes and Shelf Life

Nano-encapsulation improves the quality of grapes via controlled release of growth regulators and antioxidants. Nair et al. (2010) demonstrated that treatment with nano encapsulated gibberellic acid (GA_3) resulted in 10% larger berries without any loss of phenolic content.

Rai & Avila-Quezada (2024) observed that the shelf life of grapes was extended by 35 d, and microbial growth was suppressed by 80% by nano-ZnO-chitosan based films.

Table 3. Effects of different nanoencapsulation systems on grape quality parameters

Nano-formulation	Quality Parameter	Effect	Source
Nano-GA_3 (capsule)	Berry size	+10%	Nair et al. (2010)
Nano-ZnO film	Phenolic compound preservation	+25%	Singh & Kalia (2019)
Nano-chitosan coating	Shelf life	21 → 35 days	Rai & Avila-Quezada (2024)
Nano-cellulose + SiO_2	Microbial growth inhibition	80%	Zhang et al. (2024)

These results confirm that nano-encapsulation systems are effective not only during production but also in postharvest quality management.

4.4. Nano-Sensor Applications: Data-Driven Vineyard Management

Nano-sensors are the basis of precision management systems in grape production. Nanosensors have the potential to measure soil moisture, leaf water potential and pesticide residue levels all at once, as reported by Singh et al. (2025). Carbon nanotube (CNT)-based nanosensor can also be utilized to detect changes of water stress at an early stage, which can be linked to automatic irrigation system, resulting in water saving by 30%, as demonstrated by Rai & Avila-Quezada (2024).

Khan et al. (2025) stated that silver nanoparticle (AgNP) based biosensor for the detection of pesticide residue on the surface of grape with a sensitivity of 0.1 ppm.

The incorporation of such sensors allows growers to make real-time decisions and further advances the digitization of vineyard practices, making "smart viticulture" a practical reality.

4.5. General Evaluation and Literature Trends

A review of more than 80 scientific articles from 2015 to 2024 highlights the following trends for the application of nanotechnology in viticulture:

1. Research on nano-fertilizers constitutes around 35% of the total publication, covering the largest research field.

2. Research on nano-pesticides has been more concentrated on biologically based nanoformulations (such as neem and chitosan).

3. There has been a tremendous growth of publications on nano-sensors in the last five years.

4. Reviews on environmental risk assessment are scarce, pointing out a major research prospect.

Overall, the literature recommends that nanotechnology offers a threefold advantage model for viticulture:

• High yield (through enhanced nutrient and water management)

• High quality (through improved phenolic stability and aroma)

• Sustainability (through reduced chemical use and lower environmental impact)

5. RISKS, ETHICS, AND REGULATIONS

Although the application of nanotechnology in agriculture and more specifically in the viticulture sector has great potential to enhance productivity, quality, and sustainability, there are still some uncertainties about the interactions between nanoparticles and biological systems or within the environment. Thus, the safe use of nanotechnology needs to be evaluated not only in the context of science, but also ethics, law and social aspects.

5.1. Environmental and Ecotoxicological Effects of Nanoparticles

The ability of the nanoformulations to work is due to their high surface area and reactivity, but these properties also could lead to potential environmental hazards. Nanoparticles emitted into soil, water and air may exert toxicity towards microorganisms, insects, and human cells (Servin & White, 2016).

Metal oxide nanoparticles, eg, ZnO, CuO, and TiO_2 were found to alter soil microorganisms. Kah et al. (2013) stated that elevated levels of nano-ZnO inhibited the activity of nitrifying bacteria by 20%, triggering temporary disturbances in the nitrogen cycle. Likewise, Khan et al. (2025) in Environmental Technology & Innovation demonstrated that nano-CuO particles persisted in vineyard soils for 60 days with a decrease of around 15% in microbial biomass. These effects generally increase with decreasing particle size below 50 nm.

However, many nanoformulations are engineered to be controlled release and biodegradable. Most nano-fertilizers were completely dissolved within 30–60 days and were taken up by plant tissues, the environment risk for long term application may be reduced by suitable formulation design Abdalla et al. (2022).

5.2. Food Safety and Consumer Health

Although the nanoparticle application in viticulture enhances the quality of production, it must be regulated in a way to guarantee the protection of consumers. Nano-pesticides or nano-fertilizers in their residual form also can be found in the harvested grapes, yet it is an agreed upon fact that most residue transforms into non-toxic, inert substances (Fraceto et al., 2016).

Servin & White (2016) were able to detect nano-ZnO and nano-Fe_2O_3 residues in the skins and pomace, although at a tenth of the value the World Health Organization’s (WHO) recommended safety limit.

Rai & Avila-Quezada (2024) observed that nano-cellulose and chitosan based coatings on fruit surface constitute a safe biopolymeric layer with no signs of toxicity. In fact, most of the nanoformulations involve the use of biodegradable polymer-based carriers such as chitosan, lignin, or polylactic acid that are naturally digested and, therefore, the risk associated with food safety is expected to be minimal.

Nevertheless, the risk of bioaccumulation (i.e., accumulation of nanoparticles in human body) is still poorly known. Therefore, the European Food Safety Authority (EFSA), and the Food and Agriculture Organization (FAO) consider it mandatory to have nanomaterials traceable along the food chain (EFSA, 2022).

5.3. Ethical Dimensions and Societal Acceptance

The acceptance of nanotechnology in agriculture is not only a scientific innovation but also an ethical issue. The confidence of farmers, consumers, and manufacturers plays a critical role in defining the extent to which this technology is accepted (Ribic-Zelenović & Spasojević, 2008).

In addition to being a technological advancement, the use of nanotechnology in agriculture raises ethical concerns. The degree to which this technology is embraced depends critically on the trust of farmers, customers, and manufacturers (Ribic-Zelenović & Spasojević, 2008).

Customers frequently associate the term "nano" with artificiality or unidentified hazards, which might result in opposition due to ignorance. According to Fraceto et al. (2016), following informative communication, customer approval of nanotechnology in agricultural goods rose from 42% to 78% in a Brazilian survey.

Among the most important ethical principles are traceability and transparency. Since transparency is essential to building consumer trust, manufacturers should properly label items that include nano-formulations. Furthermore, different labeling schemes like "nano-free" can act as ethical options to accommodate diverse consumer preferences.

5.4. International Regulations and Legal Framework

There are still no global guidelines on nanotech application to agriculture products, but significant regulatory development has been made in the European Union (EU), the United States, and in the international arena through the FAO.

European Union

The EU introduced a legal definition for the term “nanomaterial” with Regulation 2011/696/EU. The European Food Safety Authority (EFSA) in its guidance of 2022 further requires that nanomaterial formulations of agricultural products are subject to the same assessments of toxicity, biodegradability and residues across the food chain prior to market authorization. Furthermore, the word “nano” must be included on any pesticide labelling which contains nano-formulations.

United States

In the US, the environmental and food safety aspects of nano-enabled agriproducts are co-regulated by the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA).

Risk assessment considerations for nano-pesticides are introduced by the EPA’s “Guidance for Pesticide Registrants on the Use of Nanotechnology in Pesticide Products” (EPA-HQ-OPP-2010-0197, 2011). Every nano-formulation is considered a scent substance with a different particle size, persistence and level of risk of exposure.

The “Guidance for Industry: Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology” (2014; revised 2022) by the FDA The report relates that Phase 2 request safety assessment for all agricultural products having nano-scale properties within a range of 1 to 100 nm.

Collectively, these two documents constitute the “Nano-Enabled Agrochemicals Regulatory Framework (EPA–FDA Model),” which serves as a benchmark for the international community (Servin & White, 2016; Fraceto et al., 2016).

FAO and OECD

The FAO’s 2021 report, “Nanotechnology in Food and Agriculture,” defined ethical and environmental values governing the use of nanotechnology in agriculture. The report defined nanotechnology as a driver of a potential “Green Revolution 2.0,” while notifying that widespread adoption without regulation and ethical oversight poses significant risks.

Türkiye

In Türkiye, nano technology-based products for agriculture are not yet specifically regulated, but they are assessed under the "Regulation on Chemical Inputs Used in Agriculture" (2023/14). The 2022 revision of the Turkish Food Codex requires labeling of "nanotechnological food additives," which could open the door for the registration of nano-formulated fertilizers and pesticides in viticulture.

5.5. Sustainability and the "Green Nanotechnology" Approach

The present scenario highlights the green nanotechnology, which promotes the use of biologically sourced materials like plant extracts, chitin, lignin for the synthesis of nanoparticles (Chhipa, 2017).

This biosynthetic approach excludes toxic chemicals as reducing agent, allowing the green synthesis of nano-formulations. For example, silver nanoparticles (AgNPs) prepared from leaf extract of *Lantana camara* were found to be effective against fungal infections without any toxic effects (Rai & Avila-Quezada, 2024).

Green nanotechnology can be promoted by circular economy model. Vineyard waste products such as pomace and vine pruning materials could be considered as lignocellulosic raw materials to produce nano-composites with high value through waste valorization.

5.6. The Importance of Risk Management, Transparency, and Regulation

Though the benefits of applying nanotechnology to grape growing are clear, the safe and ethical use of this technology should be based on three key tenets:

Scientific transparency: Unregulated data sharing on the environmental fate and toxicokinetic of nanomaterials.

Ethics and legal conformity: Respect for the risk analysis and labeling procedures recommended by the EFSA and FAO.

Public engagement: Promote and empower informatics systems for producers and consumers. If nanotechnology could be developed along the lines of these principles, it would be not only a tool of productivity but a sustainable, ethical model for future viticulture.

6. FUTURE PERSPECTIVES AND RESEARCH GAPS

At the start of the twenty-first century, nanotechnology in viticulture was essentially a theoretical laboratory science, but now it has come to be considered a strategic instrument in the revolution of agricultural production. Nano-fertilizers, nano-pesticides, nano-encapsulation systems, and nano-sensors together enhance efficiency, quality, and sustainability in modern vineyard management. Nevertheless, even though the pace of progress has been so fast, there are still many scientific, technical, and ethical research gaps to be filled.

6.1. Green Nanotechnology and Bio-Based Production Approaches

In the viticulture of the future, "green nanotechnology" will be at the heart of sustainable production. This method relies on the biosynthesis of nanoparticles utilizing plant, microbial, or agricultural waste material.

Traditional chemical reduction methods involve harmful solvents, high energy consumption, and unwarranted risks, while green synthesis offers cost-effective and environment friendly alternatives via biological reduction (Rai & Avila-Quezada, 2024).

The silver nanoparticles (AgNPs) produced by *Vitis vinifera* (grape) leaf extract reveal excellent anti-fungal property and do not produce any toxic residues after use. In the same way, lignocellulosic nanocomposites derived from vineyard pruning waste can be used as soil enhancers and as biodegradable films, making a positive contribution to the sustainable management of the vineyard (Singh et al., 2025).

Green nanotechnology is also twin with circular economy. The development of nanomaterial using vineyard by-products (pomace, seeds, and leaves) also add to waste disposal and economic empowerment. In that regard, green nanotechnology is the enabler for the future vision of "zero waste viticulture."

6.2. IoT, Artificial Intelligence, and Nano-Sensor Integration

In the techno-rural advancement of viticulture, nano-sensors represent the least size scale but a highly critical component of the Internet of Things (IoT) framework. New generation nano-sensors are anticipated to provide real time data wirelessly (Parameswari et al., 2024, Yasir et al., 2025) to monitor soil moisture and nutrient status, EC of leaves as well as presence of pathogens etc.

The intelligence (AI) of such data acquired from the sensors can also tell when to water, fertilize and apply pesticides and when to do these activities would be the most effective. Khan et al. (2025) developed CNT based nano-sensors for early detection of water stress for water saving up to 28% in AI based irrigation schemes.

Soon, "smart nano-monitoring systems" will become the standard in vineyard management, with each vine at the root or leaf level individually monitored. So, this is going to be a precision viticulture - the truth in the result based on nanotechnological.

Moreover, the IoT, nano-sensor, and blockchain-based food traceability system will create a full range production-to-consumer transparency. From the type of nano-fertilizer to the weather, to somehow soil, to just about everything in the making of the wine could be tracked digitally for every bottle. bottle.

6.3. Smart Nano-formulations and Controlled Release Systems

New evidence suggests that the next generation of nanotechnology will be geared toward not only making particles smaller, but also smarter in release systems.

These systems react to plant stress signals (pH, temperature, oxidative stress, among others) and the release of active compounds is limited to the moment they are really needed. Abdalla et al. (2022) has shown that the pH-responsive nano-fertilizers only dissolved and released the nutrient in acidic soil condition leading to a minimum nutrient loss. Similarly, photo-activated nano-pesticides that are only active in the presence of sunlight, are also emerging as an ingenious solution to reduce the unnecessary chemical load on the environment (Zhang et al., 2024).

Such "smart nano-formulations" are expected to decrease viticultural environmental footprints and facilitate "minimum input – maximum yield" precision-based principles.

6.4. Data Standardization and Regulatory Gaps

The rapid introduction to the market of agriculture products based on nanotechnology creates a potential challenge for regulation. Each country has its own requirements for classifying nanoparticles, toxicity testing and analyzing residues. For example, the EU considers "nanomaterials" to be those that fall within the size range of 1–100 nm (2011/696/EU), while the U.S. Environmental Protection Agency (EPA) considers functional nanoscale structures to be one among the same classification.

Servin & White (2016) and Kah et al. (2013) pointed out that the major gap in research is in long term surveillance of nanoparticle behavior in the environment. The processes of transformation of nanoparticles in soil and in plant matrices are still not well known.

Thus, the elaboration of the "nano-surveillance protocols" in the next years will be critical, particularly for the maintenance of long-term productivity of perennial crops as the grapevine.

6.5. Socio-Economic Dimension and Technology Transfer

The widespread application of nanotechnology in grape production is dependent upon not only scientific advancement but also the economic and educational capabilities of the producers. Ribic-Zelenović & Spasojević (2008) stated that the barriers to nanotechnology-based agriculture in developing countries are high cost of production and unavailability of technical know-how.

In the longer term, public institution/university/industry collaboration may be oriented towards the development of technology transfer centers and training of farmers in use of nano-formulations, use of sensors, and environmental management.

These policies would help enable nanotechnology to move out of the research laboratory and become a practical technology at the farm level.

6.6. Future Research Priorities

Following the tendencies in scientific literature, the next research issues in viticulture to be put in priority after 2025 are the following:

1. Long-term soil effects of nano-formulations
2. Nano-biosensors data integration using IoT
3. Studies at genomic level of plant–nanoparticle interactions
4. Comparative toxicity studies on green synthesized nanoparticles
5. Smart labeling and traceability systems based on nanotechnology
6. Carbon crediting of nanotechnology applications

These developments will redefine the role of nanotechnology in viticulture — not only through yield but also in climate adaptation and food security.

The standard for the development of innovative nanotechnology in viticulture will be set in the future by not only the improvement of yield and quality but also by ecological, digital, and ethical sustainability.

Green synthesized nanoparticles, nano-sensor networks interfaced with IoT and AI and international regulatory consensuses will form the pillars of the "intelligent, green and traceable production" paradigm in post-2030 viticulture.

The knowledge- and education-based, ethics -empowered change will be a bold new "nano-revolution" era in viticulture.

7. CONCLUSIONS AND RECOMMENDATIONS

The use of nanotechnology in the vineyard is a new ideology that modernizes the culture and methods of production. Nano-fertilizers (NFs), nano pesticides (NPs), nanoencapsulation system and nano-sensors, used in every stage of production, significantly affect the productivity, quality, and sustainability. However, the development of this technology to its full extent is dependent on the reinforcing of its scientific, ethical, and legal bases concurrently.

7.1. General Conclusions

The observations and literature reviewed within this research suggest that nano technology can be considered to have wide reaching implications for viticulture:

1. **Yield Improvement:** Nano-fertilizers improve nutrient use efficiency due to targeted and slow nutrient release and enhance plant nutrient uptake efficiency by 15–25% (Zhang et al., 2024; Kour et al., 2025).
2. **Quality enhancement:** Nano-encapsulation enhances fruit quality by increasing the stability of phenolic compounds and antioxidant activity (Nair et al., 2010).
3. **Sustainability:** Nano-formulations reduce the application of chemicals, protect the soil microbiota and the environmental footprint (Abdalla et al., 2022).
4. **Pest management:** Nano-pesticides have selective modes of action, which are effective in controlling pathogens and pests, and reduces the frequency of application by 50% (Khan et al., 2025).
5. **Digital Transformation:** Nano-sensors along further IoT-based data systems can lead to 30% water and fertilizer use savings (Parameswari et al., 2024; Yasir et al., 2025). Together, these results demonstrate that nanotechnology is not a passing trend, but a foundation for sustainable production systems in viticulture.

7.2. Scientific and Technological Perspectives

Nanotechnology intervenes at precision level in plants, which has an excellent prospect in plant science beyond the traditional approaches. Research directions in the future should be:

• *Green synthesis approaches*: Production of biologically derived NPs through environmentally friendly processing.

• *Smart nano-formulations*: Controlled release and delivery systems responsive to stressors (e.g., pH, temperature, relative humidity, and light).

• *Genomic analysis*: Study of nanoparticle–plant interactions at the level of the genome.

• *AI-enabled vineyard management*: Machine analyses of nano-sensor-generated data.

These new technologies will bring us further from traditional viticulture and into a “nano-informatic production ecosystem” that will enable us to make data-informed decisions at every stage, from grapevine to grape juice to wine quality.

7.3. Ethical and Legal Compliance Recommendations

The implications of applications of nanotechnology extend beyond technical innovation, to issues of public trust and ethical responsibility within society. The following policy actions are suggestions:

1. *Clear labeling*: Products from agriculture developed with or containing nano-formulations must be labeled with the indication “nano ingredient” (EU 2011/696/EU).

2. *Monitoring food safety*: Analyses of residues of nano-formulations should be regularly performed post-harvest (EFSA, 2022).
3. *Education and technology transfer*: Agriculture consultants and producers need to be involved in educating on nanotechnology applications.
4. *National legislation*: Türkiye should adopt a specific legal regime to register nano-based fertilizers and pesticides.
5. *Awareness*: Organize information campaigns on the risks and benefits of nanotechnology.

These measures will help ensure that the integration of nanotechnology into agriculture is safe and responsible.

7.4. Economic and Sectoral Recommendations

The implications of application in viticulture are the R&D cost, the production cost and the commercialization of nanotechnology. The following strategies are proposed for small and medium sized vineyard enterprises:

• Publicly financed pilot projects for the field-testing of nano-fertilizers and nano-pesticides need to be initiated.

• University–industry partnerships should be enhanced to share academic knowledge with practice and create shared testing centers.

• Green innovation funds should finance startups working on bio-based nano-formulations.

• Export potential should be tapped, as production free from residue enables access to the EU market making it more competitive in viticulture

7.5. Final Remarks

Nanotechnology is transforming grape growing, allowing for a more efficient and environmentally safe system of production that can be tracked. The vineyard manager of the future will be closer to a scientist, reading data from nano-sensors, understanding how plants respond on a molecular scale and adjusting production accordingly. Ultimately, largescale sustainable agricultural development using nanotechnology is not a matter of option but of obligation. Given the right regulations, ethical considerations, and scientific collaboration, this technology will be the center of a revolution that will please both the producers and the consumers.

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CHAPTER 3

SEED PRIMING APPLICATIONS IN VEGETABLE SEEDS – A REVIEW

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It is projected that the global population will reach 9.6 billion by 2050, making higher yields in horticultural crop production indispensable (Searchinger et al., 2013; Zulfiqar et al., 2020). Moreover, environmental fluctuations driven by climate change are increasingly challenging the maintenance of current food production levels. In this context, the first step toward successful crop establishment in commercial horticulture is the rapid, efficient, and uniform germination of seeds, leading to the development of vigorous seedlings. Vegetable species are gaining increasing global importance due to their provision of essential nutrients and their beneficial effects on human health. Rapid germination and robust early seedling emergence are among the most critical stages for efficient vegetable cultivation. As emphasized by researchers and growers, successful crop establishment is largely associated with high germination rates and strong seedling vigor (Chivasa et al., 1998; Murungu et al., 2004; Noor et al., 2013). Therefore, ensuring a strong start in vegetable production not only reduces the adverse effects of post sowing stresses but also forms the foundation for achieving higher yields in later stages.

Sustainable crop production requires the implementation of advanced and innovative cultivation strategies to meet the increasing food demand both locally and globally (Soubhagya Behera, 2016). Within this framework, methods aimed at improving seed germination success, early plant growth, and crop establishment have long been central to scientific research. The germination process is a multi-stage biological mechanism that begins with imbibition, followed by an activation phase in which metabolic processes are reinitiated and cellular repair mechanisms occur, and ultimately concludes with radicle emergence (Rajjou et al., 2012). Controlled exposure of seeds to water prior to the natural onset of this process is defined in the literature as “priming” (Bradford, 1986).

Seed priming is a low-cost and effective pre-sowing technique that allows seeds to imbibe a limited amount of water without reaching full hydration. This technique, which includes various approaches such as hydropriming, osmopriming, matrix (drum) priming, halopriming, as well as chemical and biological priming, prepares the seed physiologically for germination before radicle emergence. As a result, the germination process becomes faster, more uniform, and occurs at higher rates, while seedling vigor and early growth performance are also enhanced (Sung et al., 2008; Paparella et al., 2015).

High seed vigor is one of the fundamental determinants of successful crop establishment in plant production. Therefore, improving vigor constitutes an important research focus from both academic and industrial perspectives. Seed priming, first defined as a systematic technique by Heydecker in 1973, is currently regarded as one of the most promising seed invigoration methods due to its ability to enhance early seedling development and increase crop yield (Pandey et al., 2017). Among the various invigoration strategies applied during the post-harvest and pre-sowing period, priming stands out for its superior effects on improving emergence rate and uniformity. Seed priming, which can be performed using different techniques and chemical agents, is considered a crucial approach that supports the germination process through controlled water uptake. This process enables the initiation of several critical metabolic events such as the activation of enzymes and the mobilization of nutrient reserves before radicle protrusion occurs (Adhikari et al., 2020).

Lin and Sung (2001) reported that pre-sowing osmopriming and hydropriming treatments in bitter gourd seeds effectively mitigated the adverse effects of unfavorable environmental conditions on germination and subsequent seedling development.

Kaur et al. (2002) indicated that priming pea seeds with water and 4% mannitol at 25°C for 12 hours increased the number of nodes and biomass accumulation in plants. The beneficial effects of hydropriming were associated with improved tissue water content, enhanced antioxidant activity, and accelerated carbohydrate metabolism (Farooq et al., 2008).

Tajbakhsh et al. (2004) conducted a study on onion seeds using various seed treatment methods and found that hydropriming under high humidity conditions reduced the mean germination time.

Araby and Hegazi (2004) examined the effects of PEG-based osmopriming in tomato seeds and reported that the most favorable results were obtained with a 7-day priming duration followed by direct sowing.

El-Mohamedy et al. (2006) demonstrated that biopriming with *T. harzianum* reduced pre-emergence root rot in cowpea by 64% and 56.3%, and post-emergence root rot by 68.0%, 60.1%, and 57.1%, 64.0%. These treatments increased fresh pod yield by 44.0% and 36.1%, whereas the increase observed with Rizolex-T was only 19.5% and 11.2%.

Khan et al. (2009) evaluated priming treatments under salinity stress in pepper and found that NaCl priming effectively alleviated the negative effects of salinity. Compared with the control, significant increases were observed in germination percentage, germination index, germination rate, vigor index, plumule and radicle length, and seedling dry weight. In contrast, mean germination time, time to 50% germination, and seedling fresh weight did not differ significantly from the control. The authors concluded that NaCl seed priming enhanced seedling vigor and establishment under salt stress conditions more effectively than non-primed seeds.

Golezani et al. (2010) examined the effects of different hydropriming durations (P1, P2, P3, and P4: 0, 7, 14, and 21 hours, respectively) on the field performance of three pinto bean (*Phaseolus vulgaris* L.) cultivars (Talash, COS16, and Khomain). The highest seedling establishment, ground cover, plant biomass, and seed yield per unit area were recorded under the P2 treatment (7 hours), followed by P3. The Talash cultivar exhibited a significantly higher mean chlorophyll content index compared with COS16 and Khomain. Additionally, COS16 and Talash showed greater ground cover, plant biomass, number of pods per plant, number of seeds per plant, and seed yield per unit area than Khomain; however, Khomain had the highest 1000-seed weight among the cultivars. Ground cover was positively correlated with plant biomass, pod number, seed number, harvest index, and seed yield, and was therefore proposed as a reliable indicator for predicting the yield potential of pinto bean cultivars. The absence of a significant interaction between priming duration and cultivar indicated that the optimal hydropriming duration for all cultivars was 7 hours.

Venkatasubramanian and Umarani (2010) conducted storage studies in tomato to compare four priming methods—hydropriming, halopriming, sand matrix priming, and osmopriming—applied at two different durations. Their findings revealed that seed viability depended on both the priming technique and the duration of application. Among the protocols tested, 48-hour hydropriming for tomato and a 3-day sand matrix priming adjusted to 80% water-holding capacity for eggplant and pepper were identified as the most effective methods.

Ghassemi-Golezani et al. (2010) further reported that hydropriming bean seeds in water for 7–14 hours could enhance plant performance.

Yazdani et al. (2011) subjected the seeds of four legume species (lentil, soybean, green bean, and faba bean) to hydropriming treatments of 0, 4, 8, and 16 hours under laboratory conditions. The duration of priming was found to exert different effects on seedling development. Sixteen hours of hydropriming enhanced germination rate, seedling dry matter, and seed vigor. In lentil, germination rate and speed were not markedly influenced by hydropriming; however, in soybean and green bean, hydropriming significantly improved seedling growth parameters. In faba bean, both 8 and 16 hour hydropriming treatments were found to be effective.

Eskandari and Kazeni (2011) evaluated the effects of hydropriming (8, 12, and 16 hours) and halopriming (1.5% KNO_3 and 0.8% NaCl solutions) on the vigor and field establishment of cowpea seedlings. According to variance analysis of laboratory data, hydropriming significantly improved germination rate, seed vigor index, and seedling dry weight. However, germination percentages of seeds primed with KNO_3 and those of non-primed seeds were statistically similar, although both exhibited higher values than seeds primed with NaCl. Overall, hydropriming outperformed other treatments in laboratory tests. Both hydropriming and NaCl priming resulted in higher seedling emergence and plant establishment in the field compared with the control and KNO_3 priming. The increase in emergence rate observed with hydropriming highlighted its simplicity, low cost, and environmentally friendly nature.

Nawaz et al. (2011) investigated the effects of halopriming on germination, seedling growth, and biochemical responses in two tomato cultivars (Nagina and Pakit). Seeds were aerated in 10, 25, and 50 mM NaCl and KNO_3 solutions for 24 hours. Halopriming with 25 mM KNO_3 produced the greatest improvements in final germination percentage, germination index, root and shoot length, and seedling fresh weight in both cultivars compared with all other treatments and the control. In both cultivars, 24-hour priming with 25 mM KNO_3 reduced the time to 50% emergence and mean emergence time, while enhancing final emergence and seedling growth. The results indicated that halopriming with different KNO_3 concentrations produced better germination and seedling development than NaCl treatments, with the most pronounced enhancement obtained at 25 mM KNO_3. The superior performance of halopriming was associated with lower electrolyte leakage (EC), higher total and reducing sugar contents, and increased α-amylase activity.

Nakaune et al. (2012) reported that salt-based seed priming synchronized germination. Typically, high salt concentrations such as 1 M NaCl are applied for extended durations. Comprehensive gene expression analyses demonstrated that, 144 hours after the onset of treatment, NaCl priming upregulated genes associated with seedling growth and stress responses, contributing to advanced and uniform germination. Furthermore, tomato seedlings from NaCl-primed seeds exhibited greater tolerance to *Ralstonia solanacearum* compared with hydroprimed and non-primed seeds.

El-Bab et al. (2013) found that biopriming with *T. harzianum* and *T. viride* significantly reduced root rot disease in green bean. Both biopriming and fungicide treatments suppressed root rot during pre- and post-emergence stages and enhanced plant growth as well as early and total pod yield. Thus, seed treatment through biopriming was proposed as a safe alternative to chemical fungicides for managing seed- and soil-borne diseases.

Entesari et al. (2013) reported that biopriming soybean seeds with the *T. harzianum* strain BS1-1 (T.h4) was highly effective, increasing seedling length, root length, dry weight, and total chlorophyll content. *T. virens* As19-1 (T.v7) enhanced iron uptake, while UTPF-5 improved zinc, nitrogen, and total protein uptake.

Abadeh et al. (2013) reported that biopriming with plant growth-promoting rhizobacteria (PGPR) enhanced grain yield and nitrogen use efficiency in red lentil compared with non-primed seeds. They concluded that nitrogen fertilizer rates and seed inoculation with PGPR significantly influenced grain yield, 1000-seed weight, number of seeds per plant, plant height, grain filling duration, grain filling rate, and effective grain filling period. The highest nitrogen use efficiency (0.75 kg/kg) was achieved with the application of 50 kg urea/ha combined with *Azotobacter chroococcum* inoculation.

Maiti et al. (2013) found that halopriming in vegetable seeds increased emergence rate, seedling vigor index, and root and shoot length in tomato and pepper more effectively than hydropriming. Under field conditions, halopriming outperformed both the control and hydropriming treatments. Furthermore, halopriming promoted early flowering and increased plant height in both crops. Notably, halopriming enhanced total yield in tomato and pepper, marking the first study to demonstrate field yield improvement in vegetable crops through seed priming.

Costa et al. (2013) investigated the effects of hydropriming in soybean seeds and its relationship with storage fungi. They reported that hydropriming improved seed quality when microbial contamination was low, whereas high fungal presence reduced the benefits of priming.

Singh et al. (2014a) examined the effects of osmopriming duration on germination, emergence, and early growth of cowpea. Treatments included osmopriming in a 1% KNO_3 solution for 6, 8, and 10 hours, and a 10-hour hydropriming control. Their results showed that osmopriming with KNO_3 produced superior outcomes in terms of germination, emergence, plant height, and dry matter accumulation compared with non-primed seeds. Both osmopriming and hydropriming improved overall cowpea performance; however, 6-hour osmopriming with 1% KNO_3 resulted in higher germination and seedling length than hydropriming.

Sharma et al. (2014) evaluated four priming methods—hydropriming, osmopriming, halopriming, and solid matrix (SM) priming—in okra (cv. Hisar Unnat). The study included 19 different priming combinations (P1–P18) and a control (P0). Hydropriming (12 hours) and SM priming using calcium aluminum silicate (1:0.4:1 seed:SM:water ratio, 24 hours) significantly improved germination percentage, seedling vigor, mean germination time, and marketable fruit yield. Hydropriming was recommended as a simple, cost-effective, and safe method, as it increased fruit yield by up to 55% compared with the control.

Singh et al. (2014a), in a study conducted in Nigeria, examined the impact of osmopriming duration on germination, emergence, and early growth in cowpea. Treatments consisted of osmopriming in 1% KNO_3 for 6, 8, and 10 hours, along with a 10-hour hydropriming control. They concluded that osmopriming with KNO_3 at different durations produced superior germination, emergence, plant height, and dry matter accumulation compared with non-primed seeds. However, osmopriming for 6 hours in 1% KNO_3 followed by pre-sowing drying was found to enhance germination and seedling height more effectively than hydropriming.

Mazed et al. (2015) investigated the effects of five different GA_3 levels (75, 150, 225, and 300 ppm, and hydropriming) on chickpea seeds. The highest plant height and dry matter content were obtained from the T3 treatment (225 ppm GA_3). This treatment also produced the greatest number of pods, number of seeds, pod length, and maximum number of seeds per pod. The highest 1000-seed weight, grain yield, and vigor index were likewise recorded under the 225 ppm GA_3 treatment.

Toklu (2015) evaluated the effects of various priming treatments (1% KNO_3, 2% KCl, 1% KH_2PO_4, 0.05% $ZnSO_4$, 20% PEG-6000, 100 ppm IBA, 4% mannitol, 100 ppm GA_3, and distilled water) on germination characteristics and some agromorphological plant traits of red lentil under both in vitro and in vivo conditions. Non-primed seeds were used as the control. GA_3 treatment increased shoot length, plant height, and seedling emergence rate, whereas KCl enhanced nodule number as well as root and shoot dry weights. $ZnSO_4$ improved yield components and grain yield under field conditions. Overall, $ZnSO_4$, GA_3, and PEG-6000 priming treatments positively influenced germination rate, germination percentage, yield components, and grain yield in red lentil.

Tufa and Nego (2016) examined bean seeds primed with different NaCl concentrations under controlled greenhouse conditions. Data were collected for standard germination, germination rate, seedling height, shoot and root length, and vigor index. NaCl concentrations significantly affected all parameters ($p \leq 0.05$), with the highest values observed in seeds primed with 0.1 M NaCl and distilled water. The lowest values occurred at 0.4 M NaCl and in non-primed seeds. Increasing NaCl concentration negatively affected most parameters. Therefore, 0.1 M NaCl priming was concluded to improve germination and seedling growth in bean.

Soliman et al. (2016) reported that seed priming with low concentrations of salicylic acid accelerated germination, improved seedling establishment, and was particularly effective under saline irrigation conditions in faba bean, enhancing both growth and yield. They further noted that priming reduced susceptibility to soil-borne pathogens.

Kundu et al. (2017) investigated the effects of IBA (10 ppm), GA_3 (10 ppm), and H_3BO_3 (0.05%) on germination and found that germination percentage increased by 5.39%, 3.53%, and 4.56%, respectively. They indicated that GA_3 (5 ppm) produced the greatest shoot length. All GA_3 treatments resulted in higher vigor indices. PEG-6000 did not provide additional benefits for germination in mung bean but did enhance root development.

Singh et al. (2016) evaluated plant growth-promoting effects in pea and reported that primed plants showed higher shoot length, root length, leaf number, and shoot and root fresh/dry weights by 35.29%, 96.49%, 28.13%, 36.10%, 146.26%, 30.17%, and 77.20%, respectively, compared with control plants.

Arun et al. (2016) assessed priming treatments with GA_3 (100 ppm), $CaCl_2$ (10^{-3} M), ammonium molybdate (10^{-3} M), KBr (10^{-3} M), $Mg(NO_3)_2$ (10^{-3} M), and $ZnSO_4$ (10^{-3} M) to improve the performance of high- and low-vigor cowpea seeds stored under high temperature and relative humidity. Treatments applied for 24 hours at 15 °C were compared with hydropriming and a dry-seed control. Priming reduced the time to 50% germination and mean germination time, and increased germination percentage in low-vigor seeds. In normal-vigor seeds, only slight increases were observed in germination energy and final germination percentage. Priming enhanced seedling vigor in both normal and low-vigor seeds in terms of seedling length, seedling dry weight, and vigor index.

Jyoti et al. (2016) applied priming with three major growth regulators (GA_3, NAA, and KNO_3) in tomato seeds. NAA negatively affected root length, whereas GA_3 and KNO_3 were effective in increasing root length. The highest germination percentage (74%) was recorded at 50 and 75 ppm GA_3. Maximum shoot length (4.83 cm) was obtained with 25 ppm GA_3, while the greatest increase in root length (3.52 cm) occurred under 1% KNO_3 priming. The highest Vigor-I index (720), based on seedling length, was recorded at 25 ppm GA_3, and the highest Vigor-II index

(1460), based on seedling dry weight, at 100 ppm GA_3. The authors concluded that GA_3 priming played a key role in enhancing germination and vigor, recommending pre-sowing GA_3 priming to produce robust, high-vigor seedlings capable of withstanding adverse environmental conditions.

Behera (2016) reported that seed priming with GA_3 increased germination by 30.56% in the tomato cultivar Utkal Kumari.

Pradhan et al. (2017) evaluated the effects of halopriming and organic priming in black gram (*Vigna mungo* L.) seeds. Treatments included a non-primed control, hydropriming (12 h in distilled water), organic priming (cow urine, coconut water), and halopriming with 1% solutions of KNO_3, KCl, and $CaSO_4$ for 12 h. The 1% KCl treatment produced the highest germination percentage (83.25%), emergence energy (78.75), seedling length (40.30 cm), seedling dry weight (0.452 g/10 seedlings), vigor index I (3358.93), and vigor index II (37.66). Both KCl and KNO_3 treatments performed markedly better than the control.

Rai and Basu (2019) investigated biopriming with *Trichoderma viride* and *Pseudomonas fluorescens* in eight okra varieties (Lalu, Arka Anamika, Ramya, Satsira, Lady Luck, Debpusa Jhar, Japani Jhar, and Barsha Laxmi). *T. viride*increased plant height to 108.21 cm and 112.25 cm in Arka Anamika in the first and second years, respectively. In the Lalu variety, it produced the highest pod length (19.01 and 19.21 cm) and pod diameter (16.64 and 16.85 mm). Total seed yield per plant was highest in Lalu (49.14 g and 51.58 g in 2011 and 2012) and lowest in Lady Luck (24.13 g and 25.69 g). The authors concluded that different genotypes respond differently to biopriming agents and that biopriming with suitable biological agents has the potential to enhance plant growth and yield components.

Monalisa et al. (2017) examined priming effects in beans and reported that germination increased from 69% in non-primed dry seeds to 72% with hydropriming. Hydropriming improved shoot and root length, seedling dry weight, and vigor indices. Biopriming with *Trichoderma harzianum* at 40% concentration for 4 hours increased germination by 13.0%, shoot length by 21.1%, root length by 20.7%, seedling dry weight by 31.6%, vigor index I by 36%, vigor index II by 48.1%, and germination speed by 58.6%. Biopriming with *Pseudomonas fluorescens* produced similarly high improvements.

Singh et al. (2017a,b) evaluated the effects of various seed priming treatments on seed quality parameters and storage viability in the pea (*Pisum sativum* L.) cultivar KPMR-522 (Jay). Nine treatments were tested:
T0: Control;
T1: *Trichoderma harzianum* 1.5%;
T2: Vitavax Power 0.25%;
T3: GA_3 50 ppm;
T4: GA_3 50 ppm + *T. harzianum* 15 g/kg seed;
T5: Sodium molybdate 500 ppm;
T6: Sodium molybdate 500 ppm + *T. harzianum* 15 g/kg seed;
T7: *Lantana camara* leaf extract 10%;
T8: Hydropriming;
T9: Bavistin 3 g/kg.

Their results demonstrated that 500 ppm sodium molybdate + 15 g/kg *T. harzianum* significantly improved harvested seed quality. Compared with the control, this treatment increased germination by 5.75% and 8.00%, shoot length by 15.37% and 13.73%, seedling dry weight by 17.03% and 16.05%, vigor index I by 13.06% and 17.96%, and vigor index II by 24.50% and 26.90%.

Vaktabhai and Kumar (2017) conducted a study to enhance seedling vigor under salt stress in tomato using three levels of halopriming [1%, 2%, and 3% KNO_3], two priming durations [24 and 48 h], and two salinity levels [EC 2.5 and 5.0]. They reported that halopriming, priming duration, and salinity level each significantly influenced most growth, nutrient uptake, biochemical, and enzymatic parameters individually and in combination. Their findings suggested that priming tomato seeds with 1% or 2% KNO_3 for 24 or 48 h could improve seedling vigor under salt stress.

Chauhan and Patel (2017) evaluated the in vitro efficacy of various biopriming treatments in chili pepper (*Capsicum frutescens* L.). Seeds were subjected to biopriming with *Trichoderma viride*, *T. harzianum*, *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Paecilomyces lilacinus* during and after imbibition. *P. fluorescens* yielded the highest germination rate (86.70%), statistically similar to *T. harzianum* applied during imbibition. The lowest infection rate was obtained with *P. fluorescens* applied during imbibition.

When used as a priming agent in *Pisum sativum* L., *Typha angustifolia* leaf extract increased phosphorus and K^+ content under salt stress, with marked improvements compared with the non-primed control (Ghezal et al., 2016). Supporting these findings, Abdel-Baki et al. (2018) showed that priming faba bean (*Vicia faba* L.) seeds with KNO_3 increased K^+ content and decreased Na^+ content under salinity stress. Al-Amri (2013) reported that shikimic acid priming increased nitrogen, phosphorus, and K^+ contents in tomato seedlings compared with the non-primed control.

In broccoli, leaves of plants derived from primed seeds exhibited higher mineral contents (sulfur and zinc) than those from non-primed seeds (Hassini et al., 2019). In another study, Hassini et al. (2017b) found that seed priming with KCl enhanced essential mineral nutrition in *Brassica oleracea* cultivars.

In broccoli and cauliflower, seed priming significantly increased potassium ion (K^+) content, and the resulting higher K^+/Na^+ ratio was identified as a mechanism for reducing salt stress (Hassini et al., 2017a). Increased stress tolerance was associated with ion transport processes across membranes. Since K^+ and Na^+ share similar transport channels, elevated K^+ levels reduced cellular Na^+ uptake, thereby mitigating the negative effects of salt stress on seed germination physiology.

Wu et al. (2019) observed that solid matrix priming enhanced the germination rate of cauliflower and broccoli more effectively than non-primed seeds under both controlled conditions and salt stress. Therefore, this method can be considered a promising germination-enhancing strategy.

In wild asparagus (*Asparagus acutifolius* L.), Porto et al. (2019) compared the effects of cold plasma seed treatment with conventional techniques such as hydropriming, chemical priming, and hormopriming. The researchers reported that pre-sowing cold plasma priming resulted in the greatest improvement in germination. Similarly, Zhao et al. (2018) demonstrated that hybrid priming (a hydro-electric technique) in onion seeds improved germination compared with both the control and single hydropriming.

Çatıkkaş (2025) found that vermicompost-based priming treatments significantly enhanced germination, emergence, and seedling development in green onion and spinach seeds. The most effective dose was 5% VC (VC2) for green onion and 10% VC (VC3) for spinach, both of which produced the highest emergence percentage and shoot/root biomass. Overall, vermicompost priming proved to be an effective and organic seed quality improvement method for both species.

In conclusion, the findings presented in the literature clearly demonstrate that various priming techniques substantially improve germination success, seedling vigor, and stress tolerance in vegetable seeds. Although the effectiveness of hydropriming, osmopriming, halopriming, biological priming, and organic priming varies among species and cultivars, these approaches collectively enhance early plant development, strengthen crop establishment, and positively influence yield components. Considering increasing climate variability and the growing need for sustainable production, seed priming represents a low-cost, practical, and highly effective quality enhancement strategy with considerable potential in modern vegetable cultivation.

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CHAPTER 4

PLANT-DERIVED BIOACTIVES FROM VEGETABLES: A NATURAL APPROACH TO COMBAT METABOLIC DISORDERS

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1. Introduction

One of the biggest challenges facing global health systems today is the increasing prevalence of metabolic disorders (such as obesity, type 2 diabetes, cardiovascular disease and hypertension). These disorders have been linked to factors such as the widespread adoption of modern diets high in calories and low in nutrients, physical inactivity and chronic inflammation (Samtiya et al., 2021). In this context, plant-derived bioactive compounds have become central to preventive and complementary therapeutic approaches.

Vegetables offer not only essential macronutrients but also a rich repertoire of secondary metabolites known as phytochemicals. While these compounds are synthesized in plants as part of natural defense mechanisms, they can exhibit a wide range of therapeutic effects on humans (Zheng et al., 2025). Polyphenols, flavonoids, glucosinolates, glucosinolates, carotenoids and alkaloids in particular stand out for their antioxidant, anti-inflammatory, anti-hyperglycemic and anti-cancer effects (Yeshi et al., 2022).

The biological effects of these compounds are multidimensional. For example, flavonols such as quercetin and kaempferol suppress inflammation and improve insulin sensitivity by reducing cellular damage caused by oxidative stress (Chen et al., 2018; Ren et al., 2019; Li et al., 2020; Jubaidi et al., 2021). Catechins such as epigallocatechin gallate (EGCG) provide protective effects on cardiovascular health by preventing lipid peroxidation (Yeshi et al., 2022). Resveratrol slows down the aging process through SIRT1 activation, while curcumin suppresses the inflammatory response by inhibiting the NF-κB pathway (Wink, 2015).

Fucoxanthin isolated from seaweed regulates adipose tissue metabolism through thermogenesis, while phlorotannins and fucosterol show effects that support glucose homeostasis (Murugan et al., 2015). Isoflavones such as genistein and daidzein are notable for both their estrogenic and neuroprotective properties (Naoi et al., 2025; Rodríguez-Landa et al., 2025; Sharma et al., 2025). Compounds such as allicin (from garlic), capsaicin (from chili peppers) and apigenin (from parsley) are also being clinically investigated for their anti-microbial, analgesic and sedative effects (Nollet et al., 2023; Riar & Panesar, 2024).

Plant proteins such as lectin can interact directly with the cell surface and exert anti-cancer effects through apoptosis and immunomodulation mechanisms (Yau et al., 2015; Huldani et al., 2022). In addition, new pharmaceutical carrier systems (natural biopolymers such as chitosan, zein, pectin) are being used to increase the bioavailability of these bioactives (Sudhakar Gomte et al., 2025; Wen et al., 2025).

Consequently, vegetable-derived secondary metabolites are promising natural agents in combating metabolic disorders, not only for their nutritional value but also for their pharmacological potential, which can affect multiple biological targets. This book chapter aims to review the classification, sources, mechanisms of action and health effects of these compounds in the light of current scientific data.

2. Vegetable-Derived Bioactive Compounds

Bioactive compounds of vegetable origin have great potential in the management of metabolic disorders due to their versatile pharmacological properties. One of these compounds, quercetin, is found in vegetables such as onions, cabbage and spinach and may be effective in the treatment of diabetes by supporting glucose regulation thanks to its potent antioxidant properties (Al Hoque et al., 2025; Vajdovich et al., 2025). Similarly, kaempferol is also found in vegetables such as cabbage and broccoli and contributes to the regulation of the immune system with its anti-inflammatory effects (Syed et al., 2023; Ali et al., 2025; Andrés et al., 2025). Epigallocatechin-3-gallate (EGCG) from green tea and broccoli prevents lipid peroxidation and forms a protective barrier against heart disease (Sun et al., 2025; Zhang et al., 2025; Zhou et al., 2025).

Another important compound, resveratrol, is naturally found in grapes and various vegetables and slows down the aging process through SIRT1 activation, while also suppressing inflammatory processes (Abaidullah et al., 2025; Roy et al., 2025). Curcumin is a polyphenol found extensively in turmeric and shows strong anti-inflammatory effects by inhibiting the NF-κB pathway and shows promise in the management of diseases such as arthritis and diabetes (Jain et al., 2025; Kannan et al., 2025).

While luteolin found in celery and green pepper shows protective effects on the nervous system; capsaicin, the active component of hot pepper, plays a role in pain management through TRPV1 receptor activation and may help increase metabolic rate (Corral-Guerrero et al., 2025; Wan et al., 2025; Yadav et al., 2025). Allicin in garlic is considered supportive in reducing the risk of hypertension through its anti-bacterial properties and vasodilator effects (Jiang et al., 2024; Sleiman et al., 2024; Rani et al., 2025).

Seaweed-derived fucoxanthin promotes fat burning by stimulating thermogenesis, while fucosterol, another marine-derived compound, contributes positively to glucose metabolism by increasing insulin sensitivity (Xiong et al., 2022; Valado et al., 2024). Genistein, one of the soy-derived isoflavones, alleviates menopausal symptoms with its estrogen-like effects; daidzein provides antioxidant protection by supporting hormonal balance (Thangavel et al., 2019; Kim, 2021).

γ-Aminobutyric ccid (GABA), found in common vegetables such as tomatoes and potatoes (Yousefi et al., 2025), offer positive effects on anxiety and hypertension as an inhibitory neurotransmitter in the nervous system (Zhou et al., 2025). Apigenin in parsley exhibits mild sedative effects by modulating GABA receptors and has potential as a natural agent in anxiety management (Caballero-Gallardo et al., 2025; Jayaram et al., 2025). Lycopene, found in tomatoes, stands out as an effective antioxidant, especially in reducing the risk of prostate cancer by neutralizing reactive oxygen species (Shanaida et al., 2025; Ur Rahman & Panichayupakaranant, 2025).

Rutin is the glycoside form of quercetin and is found in citrus fruits and green leafy vegetables. It reduces vascular permeability, prevents capillary fragility and promotes vascular health (Regolo et al., 2024; Al Hoque et al., 2025). Myricetin is a flavonoid found in grapes and spinach; in addition to its antioxidant properties, it shows potential neuroprotective effects by protecting neurons against oxidative stress (Pluta et al., 2021; Pereira et al., 2025).

Digitoxin is a cardiac glycoside derived from *Digitalis purpurea*. It increases cardiac muscle contractility and is used in the treatment of cardiac failure but should be administered with caution due to the risk of toxicity. Camptothecin triggers the death of cancer cells by blocking DNA replication as a topoisomerase I inhibitor (Graafsma et al., 2025; Karakoti et al., 2025).

Natural products such as vinblastine and taxol stop cell division by targeting mitotic spindle strands. These compounds are FDA-approved anti-cancer drugs and have structural similarities to compounds isolated from many vegetable and herbal sources (Jan et al., 2025; Karagil et al., 2025). Hypericin is derived from the St. John's Wort plant and is being studied in cancer treatment in photodynamic therapy as well as anti-depressant effects (Fiegler-Rudol et al., 2025)

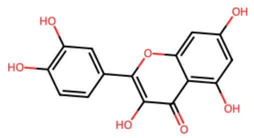
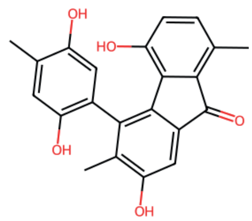
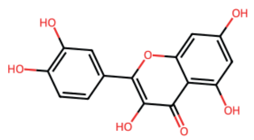
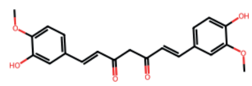
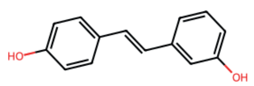
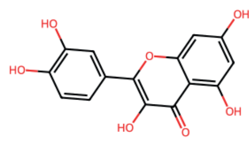
Sinigrin is a glucosinolate found in the mustard family (Brassicaceae) and may be protective against cancer by triggering cellular detoxification processes (Aboulthana et al., 2025; Ferara et al., 2025). Pectin is a soluble fiber abundant in vegetables such as apples and carrots; it reduces cholesterol absorption by increasing intestinal viscosity and provides glycemic control (Braun & Bunzel, 2025; Haider et al., 2025).

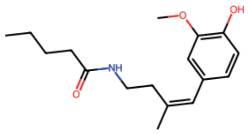
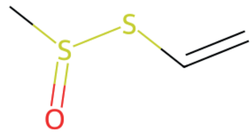
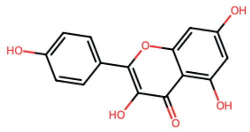
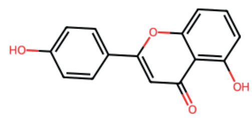
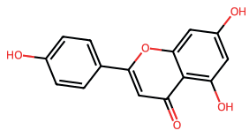
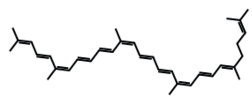
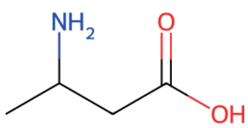
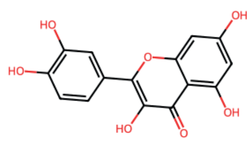
Chitosan is a biopolymer derived from mushrooms or shellfish and found naturally in some vegetables (Rad et al., 2025; Sierra 2025). It is widely used in drug delivery systems due to its ability to adhere to the intestinal mucosa. Zein is a protein derived from corn and is preferred in controlled release systems due to its hydrophobic nature (Hassan et al., 2025; Sudhakar Gomte et al., 2025).

Betalains are pigments found in colorful vegetables such as beets (Krishnakripa & Thoppil, 2025). They have both antioxidant and anti-cancer effects (Sabir et al., 2025). Lectins are carbohydrate-binding proteins found in some vegetable proteins that modulate the immune system and are especially promising in cancer immunotherapy (Padiyappa et al., 2025; Pallar et al., 2025).

3. Chemical Structure of Bioactive Compounds

The chemical structure of bioactive compounds of vegetable origin is one of the main factors directly determining their pharmacological effects. Structural factors such as functional groups, ring systems, polarity and stereoisomeric properties modulate their antioxidant, anti-inflammatory, anticancer and metabolic effects. The molecular structures of some common bioactive compounds are presented visually in Figure 1. Understanding these structures is critical for both mechanistic biochemistry and pharmaceutical formulation studies. The molecular structures of some common bioactive compounds are presented visually in Figure 1.

Quercetin  Formula: $C_{15}H_{10}O_7$ IUPAC: 2-(3,4-dihydroxyphenyl)-3,5,7-trihydroxy-4H-chromen-4-one	Hypericin  Formula: $C_{30}H_{16}O_8$ IUPAC: 1,3,4,6,8,13-Hexahydroxy-10,11-dimethylphenanthro[3,4,5,6-fgh]perylene-7,14-dione
Kaempferol  Formula: $C_{15}H_{10}O_6$ IUPAC: 3,5,7-Trihydroxy-2-(4-hydroxyphenyl)-4H-1-benzopyran-4-one	Curcumin  Formula: $C_{21}H_{20}O_6$ IUPAC: 1,7-Bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione
Resveratrol  Formula: $C_{14}H_{12}O_3$ IUPAC: 3,5,4′-Trihydroxystilbene	Luteolin  Formula: $C_{15}H_{10}O_6$ IUPAC: 2-(3,4-dihydroxyphenyl)-5,7-dihydroxy-4H-chromen-4-one
Capsaicin	Allicin

 Formula: $C_{18}H_{27}NO_3$ IUPAC: N-[(4-hydroxy-3-methoxyphenyl) methyl]-8-methylnon-6-enamide	 Formula: $C_6H_{10}OS_2$ IUPAC: Diallyl thiosulfinate
Genistein  Formula: $C_{15}H_{10}O_5$ IUPAC: 4′,5,7-Trihydroxyisoflavone	Daidzein  Formula: $C_{15}H_{10}O_4$ IUPAC: 4′,7-Dihydroxyisoflavone
Apigenin  Formula: $C_{15}H_{10}O_5$ IUPAC: 4′,5,7-Trihydroxyflavone	Lycopene  Formula: $C_{40}H_{56}$ IUPAC: ψ,ψ-Carotene
GABA  Formula: $C_4H_9NO_2$ IUPAC: 4-Aminobutanoic acid	Myricetin  Formula: $C_{15}H_{10}O_8$ IUPAC: 3,3′,4′,5,5′,7-Hexahydroxyflavone
Digitoxin	Camptothecin

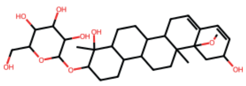
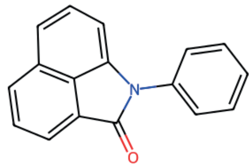
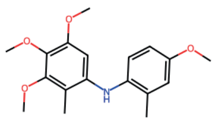
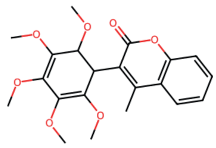
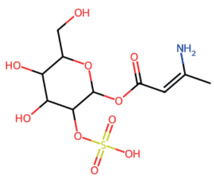
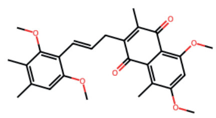
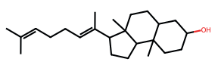
 Formula: $C_{41}H_{64}O_{13}$ IUPAC: 3β-[O-2,6-dideoxy-β-D-ribo-hexopyranosyl-(1→4)-O-2,6-dideoxy-β-D-ribo-hexopyranosyl-(1→4)-2,6-dideoxy-β-D-ribo-hexopyranosyl] digitoxigenin	 Formula: $C_{20}H_{16}N_2O_4$ IUPAC: 4-ethyl-4-hydroxy-1H-pyrano [3',4':6,7] indolizino[1,2-b] quinoline-3,14(4H,12H)-dione
Vinblastine  Formula: $C_{46}H_{58}N_4O_9$ IUPAC: Methyl (5β,12β,19α)-15-(acetyloxy)-3-hydroxy-16-methoxy-1-methyl-19-(methylamino)-6,7-didehydrovinblastine	Taxol  Formula: $C_{47}H_{51}NO_{14}$ IUPAC: Paclitaxel
Sinigrin  Formula: $C_{10}H_{16}NO_9S_2$ IUPAC: Potassium (2E)-2-propenyl-1-thio-β-D-glucopyranoside-6-sulfate	Fucoxanthin  Formula: $C_{42}H_{58}O_6$ IUPAC: 3-Acetoxy-5,6-epoxy-6′-butenolide-7′,8′-dihydrofucoxanthin
Fucosterol  Formula: $C_{29}H_{48}O$ IUPAC: (24Z)-Stigmasta-5,24(28)-dien-3β-ol	

Figure 1. Chemical structures of bioactive compounds of vegetable origin

4. Effects of Bioactive Compounds on Human Health

The effects of vegetable-derived bioactive compounds on cardiovascular health were reviewed in detail in journal articles published in many high impact factor journals (Elsevier, Springer, Taylor & Francis, Wiley, and MDPI) in recent years.

4.1. Cardiovascular Diseases and Bioactive Protection

Bioactive compounds from vegetables play an important role in the prevention of cardiovascular diseases such as atherosclerosis, hypertension and dyslipidemia. These compounds generally have antioxidant, anti-inflammatory and endothelial function-regulating properties (Chen et al., 2025; Roşian et al., 2025).

For example, lycopene, one of the carotenoids found in tomatoes (*Solanum lycopersicum*), slows the development of atherosclerosis by preventing plasma low-density lipoprotein cholesterol (LDL-C) oxidation (Daniello et al., 2024; Okoi et al., 2024). Shafe et al. (2024) reported that lycopene improves endothelial function by reducing oxidative stress in vascular cells (Jafari et al., 2025).

Onions and garlic (*Allium* species) contain allicin, a potent organosulfur compound (Corona-España et al., 2025; Singh et al., 2025). Allicin reduces vascular inflammation while lowering blood pressure like ACE inhibitors (Tian et al., 2025). It also shows antithrombotic effect by suppressing platelet aggregation (Mollahosseini et al., 2022).

Dark green vegetables such as spinach, kale and broccoli are rich in flavonoids (e.g. kaempferol, quercetin). These compounds increase nitric oxide production and promote vasodilation by supporting endothelial Nitric Oxide Synthase (eNOS) activity in endothelial cells (Ali et al., 2025; Iqbal et al., 2025). Additionally, vegetables high in anthocyanins (e.g., red cabbage, eggplant) reduce inflammation in vascular cells and balance vascular permeability (Noman et al., 2025). These flavonoids can suppress proinflammatory cytokines through the inhibition of the Nuclear Factor kappa B (NF-κB) pathway (Gao et al., 2025; Shen et al., 2025). Due to these multifaceted effects, vegetable consumption is considered a complementary strategy to medical treatments in the prevention of cardiovascular disease (Bredehorst et al., 2025; Marques-Vidal et al., 2025; Molani-Gol et al., 2025).

4.2 Neurodegenerative Disorders and the Protective Effects of Vegetable-Borne Bioactives

Naturally occurring bioactive compounds in vegetables are emerging as potential therapeutic agents for the prevention of neurodegenerative diseases (especially Alzheimer's and Parkinson's). The main pathophysiological mechanisms of these diseases include oxidative stress, neuroinflammation, mitochondrial dysfunction and epigenetic changes. Compounds such as polyphenols, carotenoids and flavonoids target these mechanisms and exert protective effects on the nervous system (Scirè et al., 2024; Hrelia et al., 2025).

Flavonoids and carotenoids, which are abundant in vegetables such as spinach, broccoli, red beets and carrots, have the capacity to reduce oxidative stress levels, especially in neurons. Compounds such as luteolin, quercetin and kaempferol have been shown to inhibit neuronal apoptosis and activate BDNF signaling pathways (Generalić Mekinić & Šimat, 2025).

Polyphenols found in vegetables, such as curcumin, epigallocatechin gallate and resveratrol, reduce the production of proinflammatory cytokines by suppressing the activation of microglia cells in neuroinflammatory processes. These effects are particularly important in the prevention of memory loss and synaptic dysfunction in Alzheimer's disease (Du & Xu, 2025; Yoon et al., 2025).

Other vegetable-derived bioactives that show promise in the treatment of Alzheimer's and Parkinson's diseases include beta-carotene, anthocyanins and glucosinolates. Through the effects of these compounds on epigenetic modifications, the progression of the diseases can be slowed (Adedara et al., 2025). In addition, sulforaphane found in vegetables such as broccoli provides neuroprotective effects by increasing antioxidant gene expression. In conclusion, the multifaceted effects of vegetable-derived bioactive compounds are considered as supportive tools in both nutrition-based and pharmacological strategies for the prevention and management of neurodegenerative diseases.

4.3 Effects on Metabolic Syndrome, Diabetes and Obesity

Bioactive compounds found in vegetables are becoming increasingly important in the prevention and management of diseases such as obesity, type 2 diabetes and metabolic syndrome, which are common metabolic disorders of modern life. Among the most important of these compounds are flavonoids, phenolic acids, carotenoids and dietary fibers; these molecules regulate glucose metabolism, increase insulin sensitivity and suppress inflammation (Mititelu et al., 2024; Santos-Sánchez & Cruz-Chamorro, 2025).

Polyphenols, which are especially abundant in vegetables, inhibit the process of obesity-related adipogenesis and play an important role in lipid metabolism. Quercetin, ferulic acid and betalain compounds found in vegetables such as broccoli, onion and red beet provide a protective effect against insulin resistance at the cellular level by reducing oxidative stress (Alvarez-Leite, 2025; Zhang et al., 2025).

Flavonoids and polyphenols derived from vegetables are known to improve mitochondrial function, suppress proinflammatory cytokine production, and support metabolic balance by regulating the gut microbiota. For example, compounds such as chlorogenic acid and sulforaphane found in microgreens have been shown to delay the development of type 2 diabetes (Dalvi et al., 2025; Shanmugam, 2024).

Vegetables with functional food potential (e.g., tomatoes, spinach, and broccoli) can reduce both the development of diabetes and the effects of obesity by supporting blood sugar regulation with components such as serotonin, betaine, and nitric oxide stimulants (Mititelu et al., 2024; Zhang et al., 2025). In conclusion, the effects of plant-derived bioactive compounds on diabetes and metabolic syndrome warrant their evaluation as functional components in preventive nutrition strategies. Regular consumption of these compounds may play a complementary role in pharmacological treatments.

4.4 Modulation of the Immune System

Bioactive compounds of vegetable origin have regulatory effects on both innate and acquired components of the immune system. Compounds such as flavonoids, phenolic acids, anthocyanins and glucosinolates have been shown to modulate cytokine production (Hernández-Ruiz et al., 2025; Tallei et al., 2025)., balance inflammatory responses and optimize immune cell functions (Kumar et al., 2025; Maqsood et al., 2025).

Glucosinolates and their derivative sulforaphane, which are highly abundant in cabbage, broccoli and cruciferous vegetables (Andrés et al., 2025; Baldelli et al., 2025), reduce the production of pro-inflammatory cytokines (e.g. IL-6, TNF-α) by suppressing the NF-κB pathway activated during the inflammatory response. These compounds are also reported to be effective on acquired immunity by increasing T cell proliferation (Wang et al., 2025; You et al., 2025).

Quercetin and anthocyanins found in onions, apples and purple vegetables suppress the activation of mast cells and control allergic and autoimmune processes by reducing histamine release (Salavoura, 2025). These compounds also support immune homeostasis by favorably affecting Treg/Th17 balance (Dębińska & Sozańska, 2023; Fu et al., 2025).

Flavonoids such as kaempferol found in spinach and lettuce increase antigen presentation capacity by regulating macrophage and dendritic cell functions. This allows for a more effective adaptive response against pathogens (Khalid et al., 2022).

For these reasons, regular consumption of vegetables not only provides vitamin and mineral support but also has multifaceted positive effects on the immune system and acts as a protective shield against the development of chronic non-communicable diseases.

4.5 Effects on Cancer

Bioactive compounds of vegetable origin are natural agents that affect the mechanisms of cancer formation in multiple ways. These compounds can prevent both the onset and progression of cancer with their antioxidant, anti-proliferative, pro-apoptotic and epigenetic regulatory properties (Casari et al., 2024; Roy et al., 2025). For example, cruciferous vegetables such as broccoli, cauliflower and Brussels sprouts are rich in glucosinolates and sulforaphane. These compounds exert anticancer effects by suppressing PI3K/Akt, MAPK and Wnt/β-catenin signaling pathways, especially in prostate, breast and colon cancers (Awasthi & Srivastava, 2024; Pal et al., 2025; Zhang et al., 2025).

Allium species such as onions, garlic and leeks contain sulfur compounds such as allicin and diallyl sulfide. These molecules limit tumor development by arresting the cell cycle and activating apoptotic pathways, especially in lung and colorectal cancer cells (Talib et al., 2024; El-Saadony et al., 2024; Wang et al., 2025).

Lycopene, found in vegetables such as tomatoes, watermelon and red peppers, prevents DNA damage (Tufail et al., 2024) in many types of cancer (Boulaajine & Hajjaj, 2024), especially prostate cancer, and increases cellular protection by reducing oxidative stress (Balali et al., 2025).

Leafy green vegetables such as spinach, kale and collard greens are rich in flavonoids such as kaempferol and luteolin (Haghighi et al., 2025). These compounds trigger cell death by acting on mitochondrial apoptotic pathways in breast and pancreatic cancer cells (Quintero-Rincón et al., 2025; Vazhappilly et al., 2025).

Anthocyanins found in dark vegetables such as eggplant, purple cabbage and black carrots neutralize free radicals and increase Caspase-3/9 activation and are effective in stomach, breast and skin cancers (Sevastre et al., 2022; Antony et al., 2025).

Beta-carotene, found in vegetables such as carrots, pumpkin and sweet potatoes, acts as a precursor of retinoic acid and slows tumor progression by supporting cell differentiation, especially in lung and liver cancers (Elsayed et al., 2025).

Including this variety of vegetables in daily diets is of great importance in terms of both preventive and treatment supportive strategies. Plant-derived bioactive compounds may increase treatment efficacy by showing synergistic effects to classical chemotherapies.

4.6 Effects on the Gastrointestinal System

Bioactive compounds of vegetable origin play important roles in maintaining gastrointestinal tract health and balancing the microbiota. Compounds such as flavonoids, polyphenols, inulin, anthocyanins and fructooligosaccharides improve intestinal barrier functions, support mucosal immunity and modulate inflammatory responses (Guerrero-Flores et al., 2024).

Especially artichoke, with its inulin and cynarin, shows prebiotic effect by promoting the growth of Bifidobacterium species. Apigenin and luteolin in celery suppress inflammation in the gut by inhibiting the production of inflammatory markers such as IL-6 and TNF-α (Ampemohotti et al., 2025).

Isothiocyanates such as sulforaphane provided by cruciferous vegetables (e.g. broccoli, cabbage) suppress inflammation by reducing the production of inflammatory cytokines (e.g. IL-6, IL-8) in intestinal epithelial cells. They also inhibit the overgrowth of pathogenic species by increasing microbiota diversity (Andrés et al., 2025; Maycotte et al., 2025).

Allicin and its derivatives, which are abundant in onions and garlic, promote the growth of lactobacilli and bifidobacteria by balancing intestinal microecology. These compounds also have a protective effect against ‘leaky gut’ syndrome by reducing intestinal permeability (Bavaro et al., 2024).

Dietary soluble and insoluble fibers act as prebiotic substrates naturally present in vegetables. By increasing the production of short-chain fatty acids (e.g. butyrate) through fermentation, they provide the energy source of colon cells and promote epithelial regeneration (Sui et al., 2025).

Red beetroot improves intestinal permeability thanks to betalain compounds, while anthocyanins in purple vegetables reduce oxidative stress in epithelial tissue (Stoica et al., 2025).

Fiber-rich vegetables such as asparagus support the growth of beneficial bacteria such as Lactobacillus and Bifidobacterium with their fructooligosaccharide content. It also regulates colon acidity and prevents the proliferation of pathogens. Cruciferous vegetables such as broccoli and cauliflower show anti-inflammatory effects on epithelial cells by suppressing the NF-κB signaling pathway through glucoraphanin-derived sulforaphane production (Ali et al., 2024).

Allicin compounds in onions and garlic stabilize the gut microbiota and prevent the growth of harmful bacteria. These compounds also have the effect of protecting intestinal integrity. Anthocyanins, found in vegetables such as eggplant, red beetroot and purple cabbage, reduce oxidative damage and promote regeneration of the intestinal epithelium (Koistinen et al., 2025). They also support gastrointestinal homeostasis by exerting an anti-apoptotic effect. Dietary fibers are common in vegetables such as carrots, spinach and artichokes, in soluble and insoluble forms. These fibers provide energy for colon cells by increasing the production of short-chain fatty acids and maintain the pH balance of the intestine (Seo, 2024; Throat et al., 2025).

4.7 Skin Health and Anti-Aging Effects

Naturally occurring bioactive compounds found in vegetables make important contributions to maintaining skin health and strengthening anti-aging defenses (Budzianowska et al., 2025). These compounds act through various mechanisms such as neutralizing free radicals, reducing inflammation, promoting collagen production and inhibiting ultraviolet (UV)-induced photoaging (Zhao et al., 2025).

Vegetables high in lycopene, such as tomatoes and watermelon, delay the formation of wrinkles by suppressing photoaging caused by ultraviolet exposure (Ma et al., 2025). These effects are associated with prevention of epidermal lipid oxidation and reduction of collagen degradation in the skin (Ibrahim et al., 2025).

Cucumber moisturizes the skin with its lignans and phytosterols content and reduces the loss of elasticity due to aging. In addition, thanks to its phenolic compounds, it suppresses inflammation in the skin and strengthens the epidermal barrier (Bauleth et al., 2025).

Flavonoids (quercetin, kaempferol) found in vegetables such as onions and cabbage keep the dermal tissue young by suppressing inflammatory responses in skin cells. These flavonoids contribute to collagen synthesis by increasing fibroblast activity (Zawawi et al., 2025).

Vegetables containing vitamin C such as spinach, parsley and peppers support collagen biosynthesis and prevent hyperpigmentation. They play an anti-spotting role by maintaining the balance of melanin in the skin (Mechchate et al., 2022).

Purple vegetables rich in anthocyanins (eggplant, purple carrots) slow down the aging of skin cells by suppressing DNA damage caused by oxidative stress. These effects are associated with their free radical scavenging activity (Maaz et al., 2025).

Red beetroot, which contains betalain, supports epidermal cell regeneration, while carrot, which contains beta-carotene, stimulates keratinocyte activity and contributes to the renewal of the epidermis (Krishnakripa & Thoppil, 2025). Thus, the skin appearance remains younger and healthier.

4.8 Antioxidant Capacity and Detoxification

Bioactive compounds of vegetable origin play important roles in enhancing the body's capacity to cope with oxidative stress and modulating detoxification processes. These effects occur by activating phase I and phase II liver enzymes and accelerating the biotransformation of toxins, while supporting antioxidant enzyme systems (SOD, CAT, GPx) (Xu et al., 2025).

Cruciferous vegetables such as broccoli, cauliflower and cabbage enhance liver detoxification capacity by increasing glutathione synthesis through compounds such as sulforaphane and indole-3-carbinol, which are released by the breakdown of glucosinolates. These compounds also activate phase II enzymes (GST, NQO1) (Ağagündüz et al., 2022; Andrés et al., 2025; Baldelli et al., 2025).

Allicin and organosulfur compounds found in garlic and onions modulate the cytochrome P450 system and support liver health by reducing free radical production. These compounds also have preventive effects against DNA damage (Kumar, 2025).

Thanks to the cynarin and inulin it contains, artichoke stimulates bile production and facilitates the removal of toxins from the digestive system (Colombo et al., 2025). It also contributes to the removal of lipophilic toxins from the liver (Nasef et al., 2025).

Spinach contains vitamins C and E and lutein, which neutralize free radicals and enhance cellular antioxidant defenses by increasing glutathione peroxidase activity. Similarly, the high vitamin C content in paprika suppresses lipid peroxidation (Alswat et al., 2024).

Phenolic compounds and betalains in vegetables such as cucumber and beetroot support liver enzymes in the detoxification process and enhance systemic cleansing with their anti-inflammatory effects (Nirmal et al., 2023).

Apigenin in celery activates superoxide dismutase and catalase enzymes, creating a protective barrier against oxidative damage. This plays a critical role in protecting tissues, especially in detox processes (Singh et al., 2024; Gaur & Siddique, 2025).

5. Overall Assessment and Future Perspectives

Bioactive compounds of vegetable origin exert far-reaching and multifaceted effects on human health. Throughout this study, the contributions of many naturally occurring compounds in vegetables such as flavonoids, phenolic acids, isothiocyanates, carotenoids and organosulfur compounds to cardiovascular protection, anti-aging, anticancer, gastrointestinal balance, microbiota modulation and detoxification processes were discussed in detail.

Vegetable consumption not only contributes to vitamin and mineral intake, but also activates defense systems such as suppressing chronic inflammation, reducing oxidative stress and activating cellular defense mechanisms. Compounds such as sulforaphane, lycopene, quercetin, anthocyanin and betalain stand out for their multifaceted effects.

However, there are some research gaps in existing literature. Issues such as the bioavailability of these compounds, their transformation processes in the gut, their interactions with microbiota and synergistic effects of different compounds are still based on limited studies. Moreover, most research is limited to *in vitro* or animal experiments and human studies are needed.

In the future, the use of these bioactive compounds in nutraceutical formulations, functional foods and personalized nutrition strategies is envisaged. Combinations of microbiota-based nutrition models and vegetable-derived compounds may form the basis of personalized dietary recommendations. In addition, bioavailability of these compounds can be increased by Nano formulation, gastro resistant carrier systems and food technology. In conclusion, the health-protective potential of natural bioactive compounds in vegetables is an area open for further research and application in the future, both from clinical and technological aspects. In this study, the potential effects of vegetable-derived bioactive compounds on human health are discussed in a multidimensional manner. Natural compounds such as flavonoids, isothiocyanates, carotenoids, organosulfur compounds and phenolic acids show numerous protective and therapeutic effects such as strengthening antioxidant defense systems, suppressing inflammation, protecting cardiovascular and neurological systems, balancing the gastrointestinal system and inhibiting the growth of cancer cells.

These naturally occurring bioactive compounds in vegetables are not only essential elements of nutrition but are also recognized as strategic biological tools for disease prevention and health maintenance. Regular vegetable consumption plays an important role in processes such as microbiota balance, anti-aging effects and detoxification. However, more human-based studies, bioavailability analyses and bioactive interaction models are needed to better understand and clinically validate the effects of these compounds. Encouraging scientific research in this direction will support the development of food-based health strategies.

In conclusion, vegetable-derived bioactive compounds are the cornerstones not only of a healthy diet but also of future personalized nutrition and disease prevention strategies.

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CHAPTER 5

VITICULTURE 5.0: A SUSTAINABLE FUTURE THROUGH THE DIGITAL REVOLUTION

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1. INTRODUCTION

Viticulture is widely regarded as one of the most knowledge-intensive agricultural activities, shaped by centuries of experimental observation, local experience, and continuous adaptation to environmental conditions. In recent decades, however, this accumulated knowledge has been increasingly challenged by climate change, resource limitations, and rising expectations regarding sustainability and transparency. Altered rainfall regimes, higher average temperatures, and the growing frequency of extreme weather events are already influencing grapevine physiology, yield stability, and wine quality across many viticultural regions (Maes & Steppe, 2018; Papadopoulos et al., 2024). At the same time, producers are expected to reduce chemical inputs, improve traceability, and comply with stricter environmental and ethical standards set by both regulators and consumers.

Digital technologies have gradually become part of vineyard management as a response to these pressures. The earlier phase of this transformation, often described within the framework of Agriculture 4.0, focused mainly on automation, sensor-based monitoring, and efficiency-oriented decision support systems (Adamashvili et al., 2024). These tools have contributed to improved operational control and resource management. Nevertheless, their strong emphasis on optimization and productivity has also revealed certain limitations, particularly with respect to ecological regeneration, social sustainability, and the long-term preservation of traditional viticultural practices (Barroso-Barroso et al., 2025).

More recently, Viticulture 5.0 has been proposed as a way for overcoming these limitations. Drawing on the wider discourse of Industry 5.0, it brings more focus on human-centered technology use, environmental friendliness and system flexibility (Ahoa et al., 2025; Mărculescu et al., 2024). Instead of challenging growers' knowledge and experience, digital tools are being seen more and more as allies that provide support in the decision-making process. Likewise, technology is a tool, which producers can use to improve human decision-making to address spatial and temporal heterogeneity within vineyards while also preserving the cultural and sensory attributes linked to terroir.

Developments in cyber-physical systems, artificial intelligence, Internet of Things (IoT) architectures, and blockchain-based traceability cover have also emerged in digital viticulture. When integrated in a coordinated manner, these technologies enable real-time monitoring of vine status, soil properties, and microclimatic patterns, as well as more transparent supply chains and data-driven predictions (Papadopoulos et al., 2024; Luzzani et al., 2021). This integration allows for a transition from corrective measures and towards a more predictive approach to management, especially under climate-related uncertainty.

Although individual digital tools are increasingly the subject of research, a holistic and integrative treatment of Viticulture 5.0 is still scarce. Most of the literature focuses on individual technologies (i.e., remote sensing, robotics, or decision support systems) without fully analyzing their complex effects in a human-centric and sustainability-driven context. In this sense, this chapter aids to synthesize the state of the art of scientific research, technological approaches and in some cases implementation exempla in Viticulture 5.0. In doing so, the chapter intends to investigate the conceptual foundation, the enabling technologies, as well as the environmental and socio-economic implications associated with viticulture, seeking to stimulate an informed debate on the future direction of this sector towards more resilient and sustainable production systems.

DIGITAL TRANSFORMATION AND THE EVOLUTION OF AGRICULTURE

Viticulture evolved over a long and fragmented historical evolution of experience, local understanding and technological innovation. With grape growing, centuries of observation and practical expertise have guided practice; in the last few decades, science and digital tools have transformed the very way vineyards are tended (Mărculescu et al., 2024). This slow change has been characterized as occurring in stages, representing a path from a rough labor-oriented type of agriculture towards more information intensive agriculture with advanced technological system support (Ahoa et al., 2025; Lezoche et al., 2020).

2.1. Traditional Viticulture (Viticulture 1.0)

Ancient viticulture was almost entirely dependent upon human and animal labor. Planting, canopy management, and harvesting in the vineyard were done by hand, according to the rhythms of the seasons, and in a close dialogue with environmental conditions (Adamashvili et al., 2024). Alcoholic fermentation of grape juice in pottery vessels from an archaeological context in the South Caucasus, in modern day Georgia, has been dated to more than 8,000 years ago. During these times, the local practice of grape growing was passed on through the generations in an informal way, influenced by the local climate, soil conditions and cultural traditions, as opposed to a system based on scientific principles (Mărculescu et al., 2024).

2.2. Mechanization and the Chemical Era (Viticulture 2.0)

The start of mechanization marked a great change, initially powered by electricity and later by internal combustion engines (Lezoche et al., 2020; Papadopoulos et al., 2024). Mechanical devices reduced the amount of work involved and led to larger vineyard areas, whereas production plans increasingly included synthetic fertilizers and pesticides. These trends brought significant improvement in production and production efficiency. However, after this widespread use, they also revealed environmental costs such as soil erosion, loss of biodiversity and increasing environmental imbalance (Mărculescu et al., 2024).

2.3. Precision Viticulture and Early Automation (Viticulture 3.0)

The integration of Information and Communication Technologies (ICT) was the first step toward a more data-driven winery management. More accurate monitoring of field operations was provided by farm machinery with electronic control units, and early automation systems enabled producers to homogenize some tasks (Ahoa et al., 2025). These early examples of technology, while still rather primitive in terms of what actually could be done, showed a shift away from mechanical systems and toward data-driven decision making that would pave the way for digital integration (Lezoche et al., 2020).

2.4. Digitization and Intelligent Systems (Viticulture 4.0)

The development of digital technologies led viticulture into what is now known as the Smart Agriculture era. With the use of sensors, IOT devices, unmanned aerial vehicles, and data analytics platforms, data collection and real-time communication in vineyard activities have been sustained (Barroso-Barroso et al., 2025; Papadopoulos et al., 2024). Decisions increasingly were made based on quantifiable metrics rather than just experience-inferred judgement. This shift changed the way vineyards were watched, managed, and controlled, by allowing more flexible and spatially differentiated management (Ahoa et al., 2025; Lezoche et al., 2020).

2.5. Human-Centric, Sustainable, and Intelligent Viticulture (Viticulture 5.0)

Viticulture 5.0 is the next transformation of which the starting point of new technologies is no longer their own use. Rather than focusing on technology for its own sake, digital systems now aim to support people, ecosystems, and long-term adaptability (Ahoa et al., 2025; Papadopoulos et al., 2024). This spirit of the age approaches the use of advanced technologies like autonomous pruning systems, laser-based weed control, or digital twin models to support biological systems without replacing those (Mărculescu et al., 2024). The focus is instead on how to build capacity and resilience, ensure resource flow, and support rural community well-being in climate-induced shock (Barroso-Barroso et al., 2025).

2. THE CONCEPT OF VITICULTURE 5.0 AND ITS CORE PRINCIPLES

Viticulture 5.0 systemizes the enabling technologies being developed under Agriculture 4.0, while intentionally striving to transcend the conceptual boundaries of mere digital efficiency. However, it argues for a manner of production where human participation, environmental sustainability, and system resilience are considered co-constitutive goals (Ahoa et al., 2025; Barroso-Barroso et al., 2025). In this context, digital technologies are not merely marginal tools but embedded elements of cyber-physical systems that are in constant interaction with biological processes across various scales (Mărculescu et al., 2024; Papadopoulos et al., 2024).

3.1. Human–Technology–Nature Interaction

Among the innovations of Viticulture 5.0 is that technology becomes a supportive ally for human decision-making instead of substitute (Papadopoulos et al., 2024). Digital platforms serve as decision-support tools that empower farmers to decode multilayered environmental signals from a distance while increasingly "being on the farm" (Mărculescu et al., 2024). This view has overtaken the classic meaning of terroir. In addition to climate and soil, unseen informational strata (i.e., soil microbial dynamics, digital modeling of environmental interactions) increasingly circulate as part of vineyard identity (Barroso-Barroso et al., 2025; Blanco et al., 2024). The combination of AI, robotics, and decades of empirical knowledge makes it possible to make management decisions at a very fine spatial scale, sometimes down to the individual vine (Contreras-Medina et al., 2025; Navone et al., 2025). This level of precision allows for interventions that are adapted to the needs of the plants, and human control is exercised to ensure that the application of technology does not interfere with cultural practices or the traditions of the winemaker.

3.2. Digital Transformation and Value-Oriented Production

In modern grape-growing, digitalization has long left post-harvest analysis far behind. Supported decision in real time, the flow of information during production is becoming increasingly transparent (Ahoa et al., 2025). For instance, traceability solutions based on blockchain technology allow for "from farm to glass" documentation that supports product authenticity and ethical production claims (Adamashvili et al., 2024; Luzzani et al., 2021). At the consumer end, e-labeling schemes give consumers detailed information on the environment indicators such as the carbon footprint, microclimatic conditions and pesticide application with transparency as a core feature of product valorization (Kasimati et al., 2024; Popovic et al., 2023).

3.3. Resilience, Flexibility and What? Sustainability-Oriented Practice

To address increasing climate variability and resource constraints, Viticulture 5.0 adopts approaches aligned with Sustainable Innovation Frameworks (SIF) (Kasimati et al., 2024). These methods, therefore, take into account the prolonged ecological viability as well as the economic one. Findings from pilot projects indicates that smart viticulture management systems can lead to a dramatic reduction in the use of pesticides, a reduction of greenhouse gas emissions and substantial savings in water (Kasimati et al., 2024; Papadopoulos et al., 2024). At the same time, enrollment in carbon credits schemes provides a further financial incentive with the annually reported earnings allowing for a more secure source of income on the farm level (Kasimati et al., 2024).

3.4. Policy Context and Institutional Support

The development of Viticulture 5.0 has been strongly influenced by agricultural policy at the European level. Tools such as the Common Agricultural Policy (CAP), the European Green Deal and Farm to Fork Strategy have nurtured certain regulatory and financial requirements aimed at promoting the adoption of digital and automation solutions (Papadopoulos et al., 2024). Besides financing mechanisms, these policies also challenge broader structural requirements such as data governance, digital literacy or the development of common communication standards that enable interoperability across technology platforms (Bastard & Chaillet, 2023; Adamashvili et al., 2024).

4. THE ROLE OF DIGITAL TECHNOLOGIES IN VITICULTURE

The wine sector is now evolving rapidly with traditional ways of making wine being pushed aside by high-tech “agro-cyber-physical systems” based on advanced digital technologies (Mărculescu et al., 2024). This change is more than just productivity enhancement and is progressively redesigning the strategic objectives of the industry such as food security, end-to-end traceability, and system-level resilience to climate uncertainty (Adamashvili et al., 2024; Barroso-Barroso et al., 2025).

4.1. The Internet of Things (IoT) and Intelligent Sensing Networks

In vineyard management, IOT is an enabler that facilitates the gathering of real-time environmental and biological information throughout the entire vineyard (Barroso-Barroso et al., 2025). Telemetric stations and sophisticated sensor networks have made them more attuned to soil moisture, microclimatic variations, and leaf wetness and better able to monitor the immediate physiological demands of grapevines, sometimes working on a highly localized basis (Kasimati et al., 2024; Ahoa et al., 2025). Alongside, bar code based digital identifiers such as RFID and QR codes which provide an end-to-end “farm-to-glass” transparency pipeline to track lifecycle/sourcing information at the level of individual wine bottles within digital platforms (Luzzani et al., 2021; Adamashvili et al., 2024)

4.2. Big Data Analytics and the Predictive Shift

The increasing availability of large-scale data streams from field sensors, orbital satellites, and unmanned aerial vehicles (UAVs) has prompted strategic shifting from reactive management to predictive modeling (Ahoa et al., 2025). Through combining historical climate data with real-time plant growth information by using sophisticated analytics, producers can predict best harvest windows, forecast yields, and manage resources more efficiently than ever before (Adamashvili et al., 2024; Barroso-Barroso et al., 2025). This data-centric strategy also leads to the decrease of production costs and energy utilization in the production procedure (Papadopoulos et al., 2024).

4.3. Artificial Intelligence and Machine Learning Applications

Artificial intelligence (AI) enables vineyard managers to analyze data at a scale and level of detail far beyond that of traditional decision-making tools (Mărculescu et al., 2024). In particular, deep learning techniques, such as the YOLO-based models, have been reported to achieve detection rates greater than 96% for the detection of vineyard disease and pests based on sophisticated image analysis techniques (Mărculescu et al., 2024; Navone et al., 2025). At the same time, pruning robots that operate without human input and ultra-precise laser based weeding systems employ machine learning-based algorithms to simulate expert decision logics, with the mentioned labor saving in the range of some 40% to 97% (Mwitta et al., 2024; Kasimati et al., 2024).

4.4. Digital Twins and Decision Support Systems

The advancement of Digital Twins (DT) technologies enables wine makers to have a risk-free "virtual workspace," in which real vineyards are digitized and replicated within completely digital solutions (Catala-Roman et al., 2024). Decision Support Systems (DSS), overwhelmed with real-time data flows from these virtual representations, provide focused and actionable advice, like the best irrigation time, or the detection of sub-zones requiring treatment (Papadopoulos et al., 2024). Real world implementations demonstrated the added value of these instruments: the FIGARO project achieved water savings up to 60%, while the vite.net system contributed to optimized pesticide application and a 33.4% reduction in greenhouse gas emissions (Kasimati et al., 2024; Papadopoulos et al., 2024).

4.5. Cloud-Based Vineyard Management Platforms

Cloud computing functions as a joined architectural layer that bring together all digital vineyard components, enabling them to be offered as service platforms to all members of the vineyard community (Ahoa et al., 2025; Hsu et al., 2020). Intended to facilitate communication between software applications while maintaining the advantage of distributed data storage, these platforms contribute to the breakdown of long-existing data silos (Agi & Jha, 2022; Ahoa et al., 2025). Growers are able to monitor vineyard conditions from a distance in real time, manage autonomous equipment, and implement blockchain solutions that provide increased transparency throughout the supply chain via cloud-based platforms (Adamashvili et al., 2024; Ahoa et al., 2025).

5. PRECISION AND INTELLIGENT VINEYARD MANAGEMENT APPLICATIONS

Precision viticulture represents a gradual shift from uniform vineyard management toward approaches that acknowledge spatial heterogeneity and biological variability within production systems. Instead of depending on generalized averages for fields, these applications bring digital tools closer to vine-specific physiological responses to enhance sustainability management and reduce unneeded environmental stress (Mărculescu et al., 2024; Adamashvili et al., 2024). However, it should be kept in mind that the precision systems' performance is still heavily reliant on local calibration, grower know-how and quality of input data, which is not always homogenous among vineyards.

5.1. Digital approaches to soil, water and nutrient management

The management of soil as a living component of the agroecosystem is at the core of Viticulture 5.0 and runs parallel to classical chemical analyses, developing into a more active way of thinking about soil functions. Microbial terroir and digital terroir have emerged as novel approaches for investigating belowground biological processes affecting vine productivity (Blanco et al., 2024). Information on the structure of bacterial and fungal communities, which may aid in future nutrient management and identify potential limiting factors in the efficiency of nutrient cycling, can be obtained from platforms like BeCrop®. Certain microbiome-based tools despite being used for health and agriculture are still predominantly descriptive and can be thought of as complementary tools rather than prescriptive. Simultaneously, IoT-based surveillance systems make it possible to monitor continuously both water and nutrient-related measures at various soil depths. These platforms provide a desirable temporal resolution; however, how useful these methodologies will be is dependent upon how information from sensors is used to make decisions in the field (Ahoa et al., 2025; Barroso-Barroso et al., 2025).

5.2. Smart irrigation and fertilization strategies

Decision Support Systems (DSS) and Variable Rate Technology (VRT) have contributed to more adaptive management of irrigation and fertilization by enabling site-specific involvements rather than uniform input applications (Papadopoulos et al, 2024). For instance, various DSS-based irrigation schedules, including those from the FIGARO project, have indicated water conservation in the range of 20 to 60%. However, such results can differ significantly with varying climate, soil characteristics and system modulations.

Similar fertilization regimes, enhanced by intelligent sensing and CTF (Controlled Traffic Farming), have been linked to better nitrogen use efficiency, in some cases by as much as 40–80%. Although these numbers show the promise of digital fertilization systems, their utilization to diverse vineyard landscapes is irregular, especially in areas that are digitally isolated (Papadopoulos et al., 2024).

5.3. Disease and pest forecasting

Models for prediction of diseases and pests supported by AI have also become increasingly incorporated into vineyard activities, with early warning and focused treatment approaches as a key outcome. Deep learning-based detection methods including recent YOLO based models have achieved high accuracy in detecting grapevine diseases with good performance both in lab environment and semi-field environment down (Barroso-Barroso et al., 2025). Pilot applications, such as those conducted in Cyprus, suggest that pesticide use may be reduced substantially (sometimes by up to 75%) when forecasting tools are combined with responsive management practices (Kasimati et al., 2024).

Although encouraging, it should be noted that model accuracy might deteriorate when exposed to different illumination, canopy structure and disease manifestation patterns. Therefore, human validation is still necessary for real-time decision-making

5.4. Yield and quality estimation

Machine learning– based yield prediction models incorporate various types of data such as vine vigor indices, water status parameters and past production information. Such techniques have improved the accuracy of pre-harvest predictions and, in a few pilot studies, have led to small improvements in quality traits like Brix (Navone et al., 2025; Kasimati et al., 2024). Yet as quality outcomes depend on a numerous of interacting elements, digital solutions are best considered as tools to support decisions rather than deterministic forecasters.

5.5. Optimization of harvest time

Digital decision support systems are increasingly allowing harvest scheduling through integration phenological observations with on-line meteorological data (Adamashvili et al., 2024). Such mechanisms enable farmers to adjust more quickly to medium-term changes in weather patterns, which has become especially important in an era of climate unpredictability. Substantial shortening of planning cycles is possible in some instances, but success will still depend upon the blending of digital guidance with local knowledge and practical experience (Sankaran, 2025).

6. REMOTE SENSING AND IMAGING TECHNOLOGIES

The non-destructive sampling at sub-canopy level enabled by remote sensing technology is nowadays a cornerstone of vineyard monitoring at large in field scale. Satellite platforms, UAS-based systems, and ground sensors also provide a three-dimensional perception of the vineyard status, although each approach is constrained by different spatial, temporal, and operational factors (Maes & Steppe, 2018; Papadopoulos et al., 2024).

6.1. Satellite-based observations and vegetation indices

Satellite imagery, especially from Sentinel-2, is a popular choice for monitoring vineyards at the regional scale, as it provides a good trade-off between spatial detail and revisit time (Laroche-Pinel et al., 2021). NDVI is still a very popular index used to assess vine vigor and within-vineyard variability. Using information from red-edge and NIR bands, satellite data can also indirectly provide information on water status of the vine and water-stress related signals. However, cloud cover and mixed pixels could limit the accuracy of the satellite-based indices at a smaller spatial scale.

6.2. UAV-based vineyard monitoring

Unmanned aerial vehicles (UAV) offer substantially higher spatial resolution than satellite platforms, enabling detailed assessment of canopy structure and inter-row variability (Khaliq et al., 2019). UAV imagery allows more accurate discrimination between vine canopy and soil background, which is particularly valuable for small and heterogeneous vineyard blocks. The growing availability of low-cost UAV systems and open-source GIS tools has further facilitated adoption, although regulatory constraints and data processing requirements can still pose practical challenges (Barroso-Barroso et al., 2025).

6.3. Hyperspectral and thermal imaging

Hyperspectral imaging is capable of providing spectral details that contribute to early identification of nutrient deficiencies and disease-induced stress prior to the occurrence of visible symptoms (Papadopoulos et al., 2024). Thermography is used to complement the method by detecting deviations in canopy temperature related to water or heat stress (Cogato et al., 2019). Although AI-enabled analysis has improved the interpretive power of these datasets, these methods often require a degree of careful calibration and remain susceptible to environmental noise (Zhang et al., 2025).

6.4. Phenology and stress assessment

Throughout growth, digital imaging systems can be used to monitor vine phenology and stress patterns continuously. Indices of spectral disease have been evidenced to be especially effective for related pathogens like *Flavescence dorée* (Syn. *Candidatus Phytoplasma vitis*) but their predictive performance depends on cultivar and environmental conditions (Al-Saddik et al., 2017). Recently, 3D point cloud reconstructions and Digital Twin methodologies have enabled the simulation of canopy architecture and fruit load, thus allowing the assessment of adaptive training systems in extreme climate conditions (Catala-Roman et al., 2024).

8. SUSTAINABILITY AND ENVIRONMENTAL IMPACTS

Viticulture 5.0 reinterprets sustainability not as a production limit but as a fundamental aspect of long-term system viability. Digital Agricultural Technologies (DATs) represent a new suite of tools that enable, but do not guarantee, the convergence of environmental and economic performance (Barroso-Barroso et al., 2025).

8.1. Carbon management and emission reduction

Measuring greenhouse gas emissions in the wine value chain is playing an increasingly important role in sustainability evaluations. Mediterranean production systems have shown that the cubic emissions of a bottle of wine can be higher than 1 kg CO_2 eq, highlighting the importance of mitigation measures (Litskas et al., 2020). DSS platforms like vite.net have shown to reduce emissions by 33.4% in pilot contexts, predominantly as a result of more efficient input use. Yet, implications such as these need to be taken with caution, as they are dependent on reference scenarios and system boundaries (Kasimati et al., 2024).

Blockchain-enabled verification of sustainable practices brings new means to access carbon credit programs. The reported positive income effects are encouraging, but these tools are still vulnerable to institutional and verification criteria (Mordor Intelligence, 2025).

8.2. Water and energy efficiency

Precision irrigation based on IoT sensors, as supported by DSS, has resulted in significant water saving with that ranging between 20 and 60% (Papadopoulos et al., 2024). Variable Rate Technology also allows for more localized management of water stress; however, the cost of infrastructure may hinder access for small farmers. In energy terms, fuel consumption decreases due to optimized routing and task execution, is not paralleled by energy efficiency improvements which depend on type of machine and scale of operation (Boiling, 2025).

8.3 Reduction in the use of chemicals

Smart pest control systems incorporate forecasting models with intervention strategies that are targeted on specific pests, limiting dependence on chemicals. Robot-assisted disease detection has enabled site-specific treatments, helping to achieve notable pesticide reductions in pilot projects (Kasimati et al., 2024). Non-chemical methods such as laser-based robotic weeding also complement these frameworks by tackling weed pressure without herbicides; however, their efficacy may be modified by species composition of weeds and growth stage (Mwitta et al., 2024).

8.4. Climate adaptation and resilience

Digital Twin simulations and predictive models increasingly support practical responses to climatic extremes. Thanks to the combination of satellite observations with ground-based measurements, these systems can predict stress conditions with several days lead time, enabling an early management response (Cogato et al., 2019). Subsurface tracking of soil microbiomes provides yet another level of resilience by maintaining biological homeostasis under duress. When linked with parametric insurance schemes, such measures facilitate not only agronomic adaptations but also financial risk management in ever more volatile climatic environs (Kasimati et al., 2024).

9. SOCIO-ECONOMIC DIMENSIONS IN VITICULTURE 5.0

Viticulture 5.0 positions technological innovation within a broader socio-economic context, where digital tools influence not only production efficiency but also labor relations, rural livelihoods, and institutional governance structures. Although cyber physical systems redefine the ways vineyards are managed, the most transformative changes are often felt beyond the level of the field, in the (re)distribution of value, responsibilities and knowledge in the wine sector (Barroso-Barroso et al., 2025).

9.1. Producer well-being and rural vitality

The adoption of digital farming technologies has slowed but steadily changed task-related work in viticulture, making the work less physically demanding and dangerous. Automation and decision-supports systems reduce direct human contact with agrochemicals and the performance of repetitive manual tasks; thereby, improving occupational safety and the long-term wellbeing of producers (Pilarczyk et al., 2025).

At a level beyond individual farms, Viticulture 5.0 potentially could simplify rural resilience via diversified sources of income. Ecosystem service-related mechanisms, such as participation in carbon credits, provide additional income that serve to mitigate market uncertainties and population decline in vineyards. However, the contribution of such arrangements to long-term rural development is still very much dependent on regional policy support and market access (Kasimati et al., 2024).

9.2. Digital literacy and human capacity

Although automation is ever growing, human labor is still fundamental to the realization of Viticulture 5.0. Factors such as education, technical knowledge, and availability of extension services are repeatedly reported to be influential determinants of uptake (Barroso-Barroso et al., 2025).

Yet, the aged structure of the farming population and differences in training access are still barriers to digital uptake. These constraints highlight the need for capacity building approaches that deliver technical training alongside user intuitive system design. User-friendly interfaces and locally adapted advisory networks are particularly important in ensuring that digital tools support, rather than overwhelm, producers (Cricelli et al., 2025).

9.3. Accessibility, scale, and inequality

Structural inequalities remain one of the most persistent challenges associated with digital transformation in viticulture. High investment costs and infrastructure requirements favor large-scale enterprises, while smaller vineyards often face barriers to entry (Bentivoglio et al., 2025). In addition, disparities in rural connectivity and the absence of standardized data protocols can reinforce regional imbalances.

In response, cooperative ownership models, shared digital platforms, and targeted public subsidies are increasingly viewed as essential instruments for inclusive innovation. Such approaches help distribute technological benefits more evenly and reduce the risk of technological concentration within a limited number of actors (Contreras-Medina et al., 2025).

9.4. Data governance and ethical considerations

As vineyards evolve into data-intensive systems, issues related to data ownership, privacy, and control gain increasing socio-economic relevance. Producers often express concerns regarding the misuse or external appropriation of sensitive agronomic information, which can undermine trust in digital platforms (Bentivoglio et al., 2025)

Blockchain-based architecture enhances transparency and traceability, yet technological safeguards alone are insufficient. Effective data governance requires clear regulatory frameworks and sector-specific ethical guidelines that balance innovation with producer autonomy and reasonable participation in digital value creation (Bastard & Chaillet, 2023; Ahoa et al., 2025).

10. IMPLEMENTATION EXAMPLES AND FUTURE PERSPECTIVES

Viticulture 5.0 is increasingly revealed in field-scale applications that integrate environmental responsibility, transparency, and human oversight alongside productivity objectives. In many areas, cyber-physical systems have risen from the experimental stage to become routinely used vineyard practices, although still to different degrees of maturity and effectiveness (Mărculescu et al., 2024)

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10.1. Regional experiences and emerging practices

Across major wine-producing regions, Viticulture 5.0 has taken shape through context-specific adoption rather than standardized technological packages. Pilot projects emphasize layered implementation strategies, where digital tools are selectively combined to address local challenges (Adamashvili et al., 2024)

In Cyprus, an IoT-based monitoring and digital labeling solution at a winery enhanced early disease detection, decreased pesticide use, and increased consumer engagement through mechanisms of transparency (Kasimati et al., 2024). Exposure to blockchain-based traceability and decision support system platforms by a cooperative winery in Italy proved beneficial in terms of improved environmental monitoring and assistance in carbon-related incentive schemes. While the claimed economic benefits are still place-specific, they demonstrate how sustainability-focused digitalization can generate additional value in positive value environments.

Türkiye’s trajectory is different but instructive: Viticulture 5.0 is in large part maturing through scientific research, pilot studies and public interventions. Variable rate irrigation and IoT monitoring research proves technically feasibility for variety terrain conditions; however, adoption on the larger scale is still hindered by infrastructure and investment capacity (Turker et al., 2020; Yavuz & Özgen, 2025).

10.2. Field-level outcomes and operational lessons

There is evidence from pilot applications that the integration of digital tools in a continuous manner can produce quantifiable environmental and operational advantages. Reported chemical input reductions, greenhouse gases emissions and administrative burden related to grape quality indicators were mild positively affected in a number of contexts (Kasimati et al., 2024; Luzzani et al., 2021).

The lessons from how things went in practice with execution are just as valuable. Data interoperability, system maintenance, and user training frequently emerge as limiting factors, highlighting the importance of long-term support structures rather than one-time technological investments.

10.3. Enablers and Barriers to the Implementation

However, Viticulture 5.0 adoption is still irregular in the face of increasing attention. Financial constraints, digital literacy shortages, and worries about data security are continuing to hinder diffusion particularly among small and medium producers (Bentivoglio et al., 2025). Policy instruments, such as CAP-related subsidies and cooperative digital infrastructure provision will be essential to reduce barriers to entry. Next-generation rural communications and edge will continue to enable better real-time decision-making and less reliance on centralized models (Mordor Intelligence, 2025).

10.4. From Control to Resilient Vineyard Systems

Management plans increasingly define future vineyards as adaptive systems, with actions derived from the interplay of human cognition and algorithmic assistance. Digital twin platforms may enable scenario planning in the face of climate uncertainty and robotic and non-chemical methods may continue to ease ecological burdens (Cogato et al., 2019; Mwitta et al., 2024). Significantly, Viticulture 5.0 does not demand the disintegration of terroir identity, but rather its reinterpretation through a hybrid intelligence that allows for the cultural heritage of wine to be maintained as well as technological progress.

CONCLUSION

Viticulture 5.0 marks a different type of transition in vineyard systems development, where digital technology is seen as a system primary infrastructure, and not just a supplementary efficiency tool. The findings discuss in this chapter highlight that modern digital applications are increasingly meeting with human-centered principles, care for nature, and systemic resilience at vineyard-scale (Ahoa et al., 2025; Papadopoulos et al., 2024).

The integration of IoT, AI, and blockchain technology has revolutionized vineyard management, shifting it from reactive approaches for problem solving to practical and transparent approaches for decision-making. They promote traceability, efficient resource management, risk management, and even build confidence between producers and consumers (Adamashvili et al., 2024; Luzzani et al., 2021). At the same time, data suggest that there is significant scope for reduced pesticide use, lower greenhouse gas emissions and water savings under well-balanced regimes of management (Kasimati et al., 2024).

However, the road to Viticulture 5.0 is neither smooth nor guaranteed. High investment costs, uneven digital literacy, and unresolved questions surrounding data governance continue to limit broader adoption. Supported by rational policy, broad innovation approaches and user-centric system design, digital transformation can escape the trap of prolonging structural inequalities within the industry (Bentivoglio et al., 2025).

Looking ahead, viticulture is likely to evolve toward hybrid management systems in which human judgment remains central, supported (but not replaced) by algorithmic intelligence. By integrating long-standing viticultural knowledge with carefully adapted digital tools, Viticulture 5.0 offers a pathway toward resilient, transparent, and ethically grounded production systems capable of responding to climate change and societal expectations while preserving the cultural essence of winegrowing.

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