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Chemical Regulation of Plant Secondary Metabolism Through Precision Agriculture and Targeted Bioactive Interventions

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ABSTRACT

The conventional agriculture is facing a two-fold crisis, it has to produce much more food and at the same time decrease dramatically the environmental impact, yet the homogeneous, input-intensive strategy does not fit the task. This review suggests a revolutionary synergistic combination of three fields in order to attain sustainable intensification. Precision Agriculture (PA) offers the data-driven nervous system to map both spatial and temporal variability of crops and soils. Developed Horticulture provides the physiological knowledge base to understand this data and use it in crop-specific management. Plant Bioactive Science proposes specific "bio-stimulatory instruments" like elicitors and biostimulants to direct plant metabolism. They then allow them to create a closed-loop approach in which spectral sensing forecasts phytochemical compositions, precision horticulture uses controlled stress to generate valuable secondary metabolites, and variable-rate technologies provide inputs with surgical precision. This paradigm changes the priority in favor of bulk yield and optimization of output and nutritional quality, taking an active role in the trade-off between biomass/biochemical product production. The barriers in terms of cost, data integration and complexities in biology still exist but the potential of sensor technology, artificial intelligence and nano delivery systems to operationalize this vision are expected going forward. This integration ultimately opens the door to phyto-chemically-optimized production systems that can achieve the highest nutritional value/unit of resource optimization which would enable agricultural innovation to meet the global food security and sustainability needs.

Keywords: Bioactive Compounds, Secondary Metabolism, Precision Horticulture, Sustainable Agriculture, Nutraceuticals

INTRODUCTION

It is the twin imperatives of global food security and sustainable intensification that creates the essential context of which the contemporary agricultural innovation should be assessed.[1] The world population that is estimated to go up to almost 10 billion by 2050 requires a significant growth in food production the estimates point to an increase of 60-70 percent of the current level in 2005. This pressure is intensely compounded by the destabilizing impacts of climatic change, which come in terms of higher occurrence of droughts, floods, heat stress and pattern changes in pestilence, which directly endanger crop stability and arable land. At the same time, there is also the paradox of agriculture upon itself: it needs to dramatically decrease its impact on the environment but increase the production. Traditional agriculture is a major source of greenhouse gas emissions, excessive utilization of freshwater, decline in biodiversity and extensive soil and water pollution by synthetic inputs.[2,3] This has created the main paradigm of sustainable intensification (SI), which is the generation of more output, with the same unit of land, water, and input and reducing environmental damage and improving the concept of ecosystem services. SI is not a technology but an objective conceptualization which requires a radical reorientation of homogeneous, input-intensive agriculture to knowledge intensive, accurate and ecologically combined management.[4,5] It is in this desperate context that the combination of three separate, but complementary fields precision Agriculture (PA), advanced Horticulture, and plant bioactive science, appears not only as a possibility, but as a systemic shift that requires evolution of our food production systems to become resilient, efficient and of high quality. Nevertheless, the prevailing paradigm of traditional agricultural activity is profoundly inadequately prepared to address the complicated needs of SI and has severe constraints on the ability to optimize yield as well as quality in a sustainable way. These restrictions are structural, based on a philosophy of standardization and application of bulk input. To begin with, the traditional management considers fields as homogenous units, which results in the indiscriminate use of water, fertilizers and pesticides. This method disregards the natural spatial differences in soil texture, nutrient levels, organic material, topography and micro climate. The effects are two fold: hefty input wastes in surplus areas that do not need them, and increased costs and pollution and sub-optimization applications in areas where they are actually needed generating yield discrepancies in the same field.[6,7] This was an inefficient use of resources that is economically and environmentally unsustainable resulting in nutrient runoffs which result in eutrophication and groundwater contamination; over-irrigation intensifies water scarcity and salinization. Second, the standard practices tend to destroy the very resource base that they rely on. Repeated ploughing enhances water-sustaining and water-filtering properties, compromising the earth structure, biodiversity and organicness of the soil-based microbes- the source of sustainable fertility. The excessive use of the chemical pesticides leads to disruption of the natural pest-predator relationships, development of resistant pest and weed biotypes, and damages non-target organisms, including pollinators which are vital to a variety of horticultural crops.[8,9]

In respect of yield, the traditional systems have arguably reached a physiological plateau of key staple crops in the prevailing management paradigm, and there is less and less input payoff. The optimization of yield is normally accomplished by utilizing genetic potential and chemical inputs, without paying much attention to the internal physiological conditions of the plant and its dynamical relation to the microenvironment. As an example, the use of nitrogen fertilizer on an interval basis as opposed to the nitrogen status and assimilatory capacity of the plant in real-time may cause luxury consumption, overgrowth of vegetation at the cost of reproductive yield and slow maturation.[10,11,12] Moreover, traditional systems are ill fitted in controlling abiotic stress on-the-fly. An impending drought or heatwave is usually dealt with on the run, and maybe not at all, with irrigation, instead of being dealt with on the proactive by physiological priming of plants to increase their intrinsic tolerance mechanisms, and result in avoidable losses in yield. The key weakness of traditional practice, especially with high-value horticultural crops, perhaps, is that it often ignores quality as a complex characteristic. The emphasis on the tonnage per hectare does not take into account the key parameters that are crucial to nutritional value, resultant shelf life, and consumer preference: concentration of health-promoting bioactive compounds (e.g., polyphenols, carotenoids, vitamins), flavor profile, texture and uniformity. These quality attributes are very sensitive to the management.[13,14] Irregular supply of water or nutrients, such as that of blossom-end rot in tomatoes or bitter pit in apples, are also the cause of a disorder. More implicitly, value-added bioactive compounds are commonly products of secondary metabolism in a plant, which is commonly enhanced in the presence of gentle, controlled stresses (eustress) a notion abhorred by the aim of conventional farming to eradicate all stress. High-input, uniform environments can maximize size and speed and yield diluted produce that is of lower nutrient density and has reduced resilience. Direct extensions of quality failures in the field are known as post-harvest losses, which have been estimated to range between 30-40% of the fruits and vegetables produced in the world, with the lower phytochemical composition of the produce or the physical integrity decomposition being more rapid.[15,16]

Fundamentally, traditional agriculture has a simplistic input output framework that is becoming increasingly inconsistent with the upheaval of plant biology, soil ecology and climate volatility.[17,18] It is offloading environmental expenses, wasting resources, homogenizing management in lieu of in-field potential, not strategically bringing the full potential of plant physiology to bear on robust yield and high quality. This challenging status quo forms an interesting problem statement: An urgent requirement is the transformative and knowledge-based framework capable of dynamically monitoring and reacting to spatial and temporal variability (PA), implementing the deep physiological knowledge to control plant performance and secondary metabolism (Horticulture), and using specific, biologically-grounded compounds to evoke the desired plant responses (Bioactives). These three pillars, combining, offer the synergistic remedy and blanket prescriptions will be substituted by the dynamic and plant-oriented dialogue thus filling the major gaps that are quite often left by traditional methods to get to the actual objectives of sustainable intensification.[19,20]

Precision Agriculture: Core Principles and Technologies

Fundamentally, Precision Agriculture is more of a paradigm shift of the traditional unified, whole-field approach to site specific, data-driven approach. It is based on the fact that it acknowledges and controls in-field spatial and temporal variability in order to achieve maximum economic returns, resource efficiency, and environmental stewardship. This is operationalized by a cycle of observation, diagnosis and action made possible by a package of interdependent technologies.[21,22] Remote Sensing is the major observational layer as it can give multi-scale information on crop status. Satellite systems (e.g. Sentinel-2, landsat) can provide synoptic, periodic images which are suitable to track seasonal patterns and regional planning. Unmanned Aerial Vehicles (UAVs or drones) support an increased spatial and temporal resolution, that is capable of yielding detailed spectral information (including both multispectral and thermal imaging) of the landscape to identify the early cues of water stress, nutrient deficiency, or disease hotspots, before they are visible to the human eye.[23]

Table 1: Core Limitations of Conventional Agriculture vs. Solutions from the Integrated PA-Horticulture-Bioactives Framework

Aspect	Limitation of Conventional Agriculture	Solution from Integrated Framework
Spatial Management	Treats field as homogeneous; blanket application of inputs	PA manages in-field variability via sensors & VRT; applies inputs site-specifically.
Resource Efficiency	High waste, pollution, and cost due to over-application.	Precise application reduces waste, lowers environmental footprint, and optimizes ROI.
Yield Optimization	Approaches physiological plateau; reactive stress management.	Proactive priming with bioactives; real-time stress mitigation via PA sensors & models.
Quality Focus	Neglected or diluted; emphasis on tonnage over nutritional density.	Active elicitation of secondary metabolites via precision horticulture & bioactives.
Soil & Ecosystem Health	Degradation through tillage, erosion, and chemical overuse.	Reduced chemical load; potential for enhanced soil biology via targeted biostimulants.
Decision Basis	Schedule-based, reactive, and empirical.	Data-driven, predictive, and based on real-time plant physiology.

The finest quality data (e.g. the electrical conductivity of soil, pH, and real-time canopy structure) is supplied by proximal sensing, which incorporates ground sensors on tractors or a stationary installation (e.g. NDVI via Greenseeker).[24,25] The multi-level sensing strategy generates the multi-layered data stream of biophysical parameters of crops. Nevertheless, raw data cannot be sufficient; it needs a framework to be interpreted and make spatial decisions. It is at this stage that Geographic Information Systems (GIS) and Spatial Data Analysis is essential. GIS can be considered as the digital brain of PA, which combines the dissimilar layers of data such as soil maps, yield histories, remote sensing indices, topography and makes them a single unified database that is georeferenced. Kriging and clustering algorithms are then used as spatial statistical methods to determine coherent management zones in an area.

These spaces identify regions of similarity and potential in place of the concept of a homogenous field to a mosaic of individual micro-managements units. The practical deliverable of this analysis is a prescription map. The physical actuator of PA is called Variable Rate Technology (VRT) which enables the inputs, such as seeds, fertilizers, lime, and pesticides, to be applied in the rates that are accurately determined according to the needs of every management zone. The agricultural machinery has a controller which translates the prescription map on the fly and automatically varies application rates as it moves across the field.[27] This guarantees that resources are distributed where they are needed the most and also where they are not needed reducing the waste that is inherent in the conventional blanket applications. Lastly, there is the transforming frontier of PA which is the Internet of Things, Sensors and Real-Time Monitoring. This can be achieved by implementing networks of in-situ wireless sensing that constantly record the important parameters including soil moisture, temperature, nutrient content, and microclimate. These sensors send information to the cloud systems through IoT gateways and as a result, real-time monitor on the dashboard is possible and most importantly automated response can be triggered. A typical example is that water loss in soil moisture within a particular area may activate an irrigation solenoid or an increase in canopy temperature may activate a special cooling mist in a greenhouse. This completes the circle between observation and action, making PA more of a dynamic, responsive system, able to respond to variations in crop crops not only spatially, but also in real time.[28,29]

Modern Horticulture: Quality-Centric Production and Physiological Production

The contemporary horticulture does not only surpass the agronomy, but pays much attention to the physiological mechanisms of plants, especially high-value fruit, vegetables, and ornamentation, with an uncompromising value on quality as the major product.[30] The field is the key to the biological knowledge base which makes the data of PA become meaningful. At its core, there is an in-depth knowledge of the Physiology of Plants and Stress Response. The complex and intertwined processes of photosynthesis, translocation, respiration and hormonal regulation, which control growth, development and yield formation are studied by horticulturists. Most importantly, they draw a line between distress (stress that is severe, and limits the yield) and eustress (stress that is mild, tend to be positive). A wide range of quality features, most notably the synthesis of bioactive products such as anthocyanins (color) or resveratrol (antioxidant) is a result of secondary metabolism, which is often induced as a protective mechanism to controlled abiotic stress (such as moderate water deficit (regulated deficit irrigation) or light spectra). The knowledge of these cause-and-effect relationships enables the growers to utilize the environments strategically to produce desired quality results in plant metabolism without the need to reduce yield.[31] The exact environmental control is idealized by Controlled Environment Agriculture and Soilless Systems including greenhouses, vertical farms, and hydroponic/aeroponic systems. CEA separates production it of external climatic variability so that year-around growing is possible, and the optimal use of temperature, humidity, light intensity, photoperiod, and spectral quality (through LED lighting) can be controlled. Recirculating nutrient mixtures (e.g. hydroponics) and soilless substrates (e.g. rockwool, coco coir) can provide unprecedented control over the root zone, providing water and minerals in specific proportions as dictated by the particular stage of crop growth. This aspect of control renders CEA an optimal testing ground and high-worth application area of integrated PA and bioactive measures since each input could be quantified and varied. Nonetheless, the success of any general technology depends upon Crop-Specific Management Practices. The physiological needs of a tomato are completely different to those of a strawberry, blueberry or a leafy green. An example is that the quality of tomato fruit is very sensitive to the proportions of potassium to calcium, and berry may need to be subjected to a certain amount of chilling in order to become dormant. This crop-specific vocabulary is accorded by modern horticulture, the knowledge of the phenological stages, nutrient requirements during flowering versus fruit set, during pollination, and during harvesting. It provides the answer to the question of why and when behind the question of where PA identifies, which means that technological interventions are biologically relevant and schedule so that they may have maximum effects on both the yield and the quality.[32,33]

Plant Bioactive Ingredients

Plant bioactive ingredients represents a wide range of secondary metabolites, which though not vital to primary growth and development, have important roles in plant adaptation, plant defense and interaction with the environment. They are used in agriculture, not just based on the old methods of nutrition (NPK) but rather in such a way that they directly impact on plant physiology at a hormonal and metabolic scale.[34,35] The compounds may be grouped into broad Definition and Classes (e.g., Phenolics e.g., flavonoids, lignans, stilbenes), which have anti-oxidant effects and protect against UV; Alkaloids e.g., caffeine, capsaicin), which are often used in defense against herbivores; Terpenoids e.g., carotenoids (lycopene, beta-carotene), essential oils (menthol), which provide defence, aroma and pigmentation; and Other classes.[36,37]

Table 2: Major classes of plant bioactive ingredients, their functions, and agricultural application potential

Class (Examples)	Primary Functions in Plant	Key Agricultural Application & Target Outcome
Phenolics (Flavonoids, Lignans, Stilbenes)	Antioxidants, UV protection, structural components, defense.	Elicited to enhance antioxidant capacity, color, and stress resistance in fruits/vegetables.
Alkaloids (Caffeine, Capsaicin)	Defense against herbivores, allelopathy.	Targeted boosting for medicinal/spice crops; potential role in induced pest resistance.
Terpenoids (Carotenoids, Essential oils)	Pigmentation, aroma, defense, photosynthesis.	Managed to improve color (lycopene), flavor/aroma, and abiotic stress tolerance.
Glucosinolates	Defense compounds (e.g., in Brassicas).	Elicited for enhanced nutritional (anticancer) properties in vegetables like broccoli.
Plant Growth Regulators & Hormones (Jasmonates, Salicylates)	Internal signaling for growth, development, and stress response.	Exogenous application to prime defense systems, modulate growth, and improve fruit set.
Biostimulants (Seaweed extracts, Humic substances)	Enhance nutrient uptake, vigor, and stress tolerance.	Precision application to improve fertilizer use efficiency and homogenize crop vitality.

Synthesis of these compounds and Biosynthesis Pathways are highly regulated and frequently stimulated by environmental or biotic stimuli (elicitors). The stimulation of such pathways as shikimic acid (phenolics) or methylerythritol phosphate (terpenoids) pathways can occur.[38,39] This is the secret of their agricultural exploitation: their production can be turned on or increased by special intervention. The means of elicitation are the application of abiotic (e.g., particular light wavelengths, controlled drought stress, nutrient salts such as silicon or selenium) or biotic (e.g., shellfish, seaweed extracts, microbial consortia useful, or even compounds inherent to plants). This transforms the natural defense and adaptation system of the plant as an instrument of control improvement.[40,41]

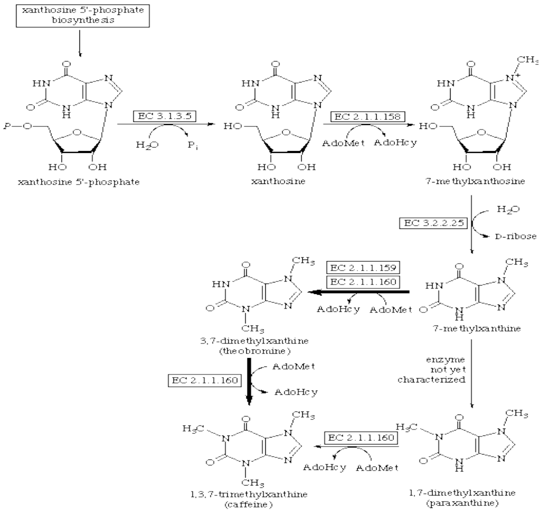

Fig. 1. Biosynthesis of Caffine by xanthine enzyme

These bioactives have a variety of Bioactivities when used exogenously: Plants Growth Regulation, Biostimulation, Stress Priming. They are not mere fertilizers but signal molecules or metabolism primers. Plant Growth Regulation implies small-scale regulation of hormonal balances (auxin, cytokinin, gibberellin) to control plant processes such as root architecture, flowering time and fruit set. Biostimulation is the improvement of nutrient uptake and use efficiency, photosynthesis rates and general plant vigor commonly observed with humic/ fulvic acid use or particular protein hydrolysate use. Stress Priming (also known as acquired tolerance) is the most powerful and is the pre-treatment of the plants with a low concentration of bioactive compound (or an elicitor) to train the plant defence mechanisms. This preconditioning activates the physiological state of the plant, resulting in a quicker, more vigorous and more effective respo[42] nse of the plant to a stress in the future such as drought, salinity, or pathogen attack. Such a preventative measure can be very effective in minimizing losses of crops and preserving quality even in harsh conditions. Therefore, plant bioactives constitute an advanced, biologically-inspired toolkit to modify the plant performance, directing it toward resilience, efficiency, and biochemically-enriched structure.[43]

Synergistic Integration: Conceptual Framework

The real transformative capacity of PA, horticultural science, and bioactives does not lie in their individual implementation, but in their planned and integrated implementation. This causes a closed-loop, intelligent crop management system, in which the whole is bigger than the sum of its parts. PA is the Information-Based "Nervous System" in this context. It offers the sensory equipment (sensors, drones) to constantly monitor the condition of the crop and the surrounding environment, and the diagnostic brain (GIS, AI) to diagnose problems and discover opportunities. Horticulture provides this as the Physiological "Knowledge Base. It views the PA data in the concept of plant biology.[44,45] It identifies the reasons that may have caused the plant to be stressed (is it a potassium shortage at fruit swell? It determines the most physiologically favorable stage to act (e.g. pre-veraison in grapes to promote anthocyanin production) and when the area is in the clay-rich region to be water-logged or not (e.g. clay-rich soils). It gives the context to the crop, transforming generic data points into biological diagnosis and a strategic goal (e.g., improve antioxidant capacity in Zone B in the upcoming heatwave). Biostimulatory tool - Bioactives then carries out the prescribed intervention as the Targeted Bio-Stimulatory Tool. Rather than a generic fertilizer or pesticide, the system orders a given bioactive cocktail; say a seaweed extract full of cytokinins and betaines to a zone with heat stress, or a chitosan elicitor to a zone with high disease risk. More importantly, VRT and IoT systems allow applying these bioactives with high accuracy and in the variable rate only when required and in the accurate amount established by the combined diagnosis.

PA recognizes micro-zones of plants undergoing (or likely to be undergoing) mild and manageable stress. Horticultural knowledge ascertains that such a zone and development stage is appropriate in eliciting. An example is to activate secondary metabolism, targeting a specific zone, with a specific bioactive, without causing a yield cost to the whole field. This is to a sub-field level of controlling eustress. Second, Predictive Protection and Resource Allocation: the IoT sensors will inform about abiotic stress (e.g., soil moisture falling) earlier. After the information of the horticultural models, the system can cause a pre-emptive delivery of a priming bioactive (e.g., salicylic acid analogue) to the respective affected rows. This preparedness adds to the natural tolerance that the plant has, making the real yield less affected by the stress when it occurs in all its fullness, hence stabilizing the yield.[46,47] The resources (water, bioactives) are distributed to the regions which require prophylaxis. Third, Use Efficiency of Nutrient Ingots: When applied to sites that PA has determined that there is poor nutrient use efficiency (e.g., regions with high nitrogen reflectance, but low biomass), the plants can be encouraged to utilize better the available nutrients in their environments, closing yield gaps and enhancing uniformity. This forms a virtuous cycle since an improvement in the health of the plants results in the increased homogeneity of the PA sensor measurements. Lastly, Dynamic Quality Optimization: In the high-value contract where a certain nutraceutical content is required, PA may track spectral indices that are associated with bioactive concentration (e.g.,anthocyanin reflectance index). With harvest at hand, when some blocks underperform against target values, horticultural expertise may be used to apply a last and focused elicitor treatment to those underperforming blocks, which will result into quality consistency and attainment of high market specifications. Finally, this unified model shifts agriculture to a form that is more reactive and input-based to a model, which focuses on plant-physiology.[48,49] The nervous system of the PA senses, the body of knowledge of horticultural knowledge understands and counseleth, and the bioactive tools implement the specifics of physiological intervention. Such synergy is bound to overcome the perceived trade-off between yield and quality, and result in sustainable intensification to ensure the future food security and nutritional needs are met.[50]

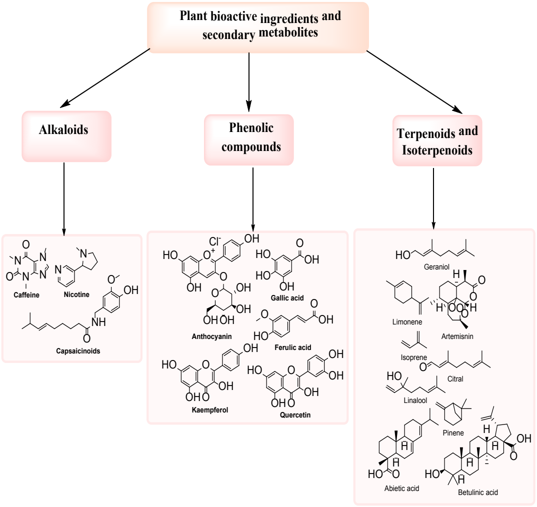

Fig. 2. Classification plant bioactive ingredients

The Convergence: mechanisms of synergistic integration

The real healing power of this triad is not in their application separately, but in their conscious combination. This brings about a closed loop intelligent management system in which data drives accurate interventions to control plant physiology, and the biochemical output is used to inform more accurate interventions. In this section, the mechanisms that allow this synergy to happen are disected starting with sensing and mapping and on to active optimization and feedback.

Mapping and Managing the Variability of Bioactive compounds PA

One of the essential problems when manufacturing plant-based bioactive components is their spatial and temporal variability within a stand of crop. The conventional bulk harvesting method homogenizes this variability, which is usually diluted in potency. Precision Agriculture offers the toolkit to map, comprehend and treat this heterogeneity as an asset, but not a liability.[51,52]

Spectral sensing for predicting phytochemical content

The backbone of such integration is the real time estimation of bioactive compounds non-destructively with the help of spectral sensing. The interaction of light and plants takes place at different wavelengths (400-2500nm) and the spectrophotometric patterns of their reflectance are the unique fingerprints that rely on the biochemical composition. Sophisticated methods of analysis remove the distance between spectral data and phytochemical concentration.[53,54] Detailed canopy reflectance data are obtained by hyperspectral and multispectral sensors on UAVs, or tractors, or satellites. There are specific compounds that have key spectral regions: e.g. anthocyanins at the green range (in the 550nm range), chlorophyll and nitrogen status at the red-edge (in the 700-750nm range), and water content and broad biochemical bonds (C-H, O-H, N-H) at the short-wave infrared (SWIR, 1000-2500nm). This connection is created through chemometrics.[55,56,57] Simultaneous spectral measurements are combined with ground-truthing, in which the samples of the plant tissue are scrutinized in the lab through HPLC or GC-MS to determine the precise amount of a specific compound. Algorithms of machine learning (e.g., Partial Least Squares Regression, Random Forest, Neural Networks) are then trained to come up with robust calibration models. Such models can then be used to forecast the concentration of target compounds (e.g. curcumin in turmeric, capsaicin in peppers, constituents of essential oils in herbs) in a wide field of spectral data alone. This allows the generation of high resolution phytochemical maps. Not only can a grower see in which plants are stressed or in which plants are actively growing, but also in which areas of the field there are high therapeutic or nutritional density. This shifts the management to a bioactivity-centric perspective as opposed to a biomass-centric perspective.

Zoning management based on biochemical phenotypes

The spectral sensing phytochemical maps are used to help switch between uniform field management to the biochemical phenotype, or zoning- based field management of plants sharing bioactive compound profiles. GIS software groups the habitat with comparable forecasted phytochemical rates into separate management groups.[58] A vineyard can be given as an example, though divided into high, medium, and low anthocyanin/polyphenol zones. This is the most immediate application. The harvesting can be planned and implemented zone-wise. Zones with high potency may be harvested singly (to produce premium lines of products e.g. single-origin or high-potency labeled extracts), low-potency zones may be sold into the regular markets. This results in the optimization of the crop and stability of nutraceutical producers. Out of harvest, such areas inform focused agronomic interventions. An area that has low-than-preferred bioactive matter can be subjected to a certain precision horticulture treatment (e.g. customized irrigation or nutrient spray), and induce production, which will be detailed in the following section. When variability is mapped, precision horticulture offers the physiological levers to act upon to manipulate plant secondary metabolism in an active manner. The aim is to use controlled, focused stresses or stimuli to upregulate biosynthetic pathways without causing a major reduction in primary yield- a principle referred to as "eustress." Secondary metabolites are a large number of bioactive compounds whose synthesis is involved in the defense against environmental stress. These stresses can be administered in a controlled dose-specific way using precision technologies. LED lights enable the precise spectral control in Controlled Environment Agriculture. Presentation of plants to a certain wavelength can significantly change the phytochemistry. An example is UV-B radiation, which is a very strong inducer of polyphenols and flavonoids (e.g. in basil and lettuce). The inclusion of the far-red light can affect morphology and secondary metabolism. PA data of actual plant response can dynamically regulate "light recipes" to optimize a particular compound. Precise drip or micro-sprinkler systems that apply strategic water stress have been shown to raise the concentration of essential oils, phenolic compounds, and antioxidants in plants such as grapes, olives and aromatic herbs by applying strategic water stress at certain phenological stages in the plant. The soil moisture sensors and evapotranspiration models are used to make sure that the stress is accurately regulated so as to induce metabolite production without leading to irreparable harm or loss in yield. Precision elicitors can also be mild temperature changes or controlled exposures to positive gases (e.g. ozone, CO_2 enrichment) directed by sensor networks.[59]

Precision nutrient management to enhance secondary metabolites

The trade-off between primary (biomass) and secondary metabolite production directly depends on nutrient availability. Precision nutrition adjusts this balance positively by increasing supply. The role of nitrogen (N) is essential; high N nitrogen levels enhance vegetative growth, however, distorting secondary metabolites. Regulated, low N level, particularly at advanced stages, tends to stimulate the synthesis of the phenolic compounds and alkaloids. Equally, the presence of phosphorus, potassium, sulfur and micronutrients such as selenium can serve as a signal or co-factor during certain biosynthetic pathways. With VRT, application of fertilizers can be done differently depending on the zoning of both desired bioactive targets and yield potential. A zone with a high bioactive potential will not have the same N:K ratio as one applied in a zone with the highest possible fresh weight yield. Strong elicitors of secondary metabolism include plant growth regulators (PGRs), biostimulants (e.g., jasmonic acid, salicylic acid, seaweed extracts), etc. They can be induced selectively on a zone-by-zone basis by their foliar application through sprayers fitted with VRT. Using the phytochemical maps, a low-potency zone may be directed using an accurate dose of an elicitor (e.g., methyl jasmonate) to stimulate pathways associated with defence, and thus increase the synthesis of desired compounds such as terpenoids or alkaloids. It eliminates the need to apply to areas high in performance, thereby reducing the input expenses and eliminating possible phytotoxicity.

Bioactive ingredients as indicators and targets for PA

It is symbiotic in nature. Similarly to the bioactive content of a product being measured and affected by PA tools, the phytochemical profile of a plant is a complex, inherent biosensor, which can be used to gain profound insights into plant conditioning that can be used to refine PA decision-making. Conventional PA uses indirect measures of stress (e.g., chlorophyll fluorescence, canopy temperature). Direct, mechanistic biomarkers are provided by specific bioactive compounds. The buildup of some antioxidants (e.g., ascorbate, glutathione) or stress-specific products may indicate the development of biotic or abiotic stress prior to the emergence of any noticeable symptoms or loss of any substantial quantity of biomass. The pre-symptomatic intervention is possible through spectral detection of these compounds. Various stressors cause different phytochemical signatures. Drought could increase the levels of abscisic acid (ABA) and proline, and herbivory could induce quick production of jasmonates and specific volatile organic compounds (VOC).

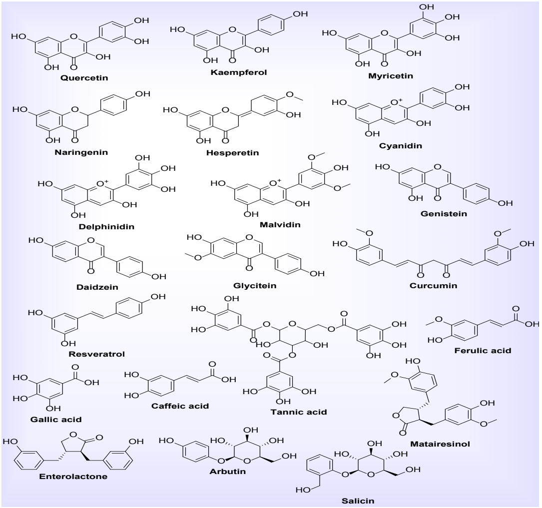

Fig. 3. Chemical Compound and its Active Ingredients

The diagnosis of stress type and degree using such spectral-biochemical signatures enables the PA to be transformed into a diagnostic and predictive system as opposed to a reactive one. The revolution is the integration of the breeding of plants in nutraceutical and functional food markets. Breeders can non-destructively and in a brief period time, screen thousands of field-grown genotypes with PA technologies especially UAV-based spectral imaging to select genotypes according to agronomic factors (biomass, height) and biochemical factors (estimated phytochemical content). This generates gigabank, spatially-referenced, genotype to biochemical phenotype real-field datasets. The breeders are able to establish plants that not only produce well but also produce desired bioactive elements in high amounts over a given regime of management (GxExM interaction). PA data can be used to find these elite chemotypes in the context of a dissimilar breeding population. Genomic selection models take input in the spatial and temporal information of phytochemical expression related to environmental and management information. This speeds up the process by which novel cultivars that are optimized to produce bioactives are developed in precision agri-horticulture systems so that genetic capability is not wasted as a result of agricultural blight.

This theoretical compatibility of precision agriculture, horticulture and bioactive compound management is operationalized by a collection of convergent technologies and new methodology paradigms. It is a change in the discrete tools towards a unified, cyber-physical system where biological processes can be tracked, comprehended and intervened with a precision and purported intent never before seen. This portion describes the fundamental technological pipelines and sophisticated procedures that help in transforming the theoretical synergy into practical farm management and research procedures.

The digital pipeline: from sensor data to bioactive optimization

A unified flow of information between the field and the cloud and back to the actuator is the key to the inner workings of the integrated system. This pipeline will turn raw environmental and plant data to predictive knowledge and, eventually, prescriptive management actions that will optimize the yield and phytochemical content. Phenotyping traditional is a bottleneck. A combination of HTP platforms and metabolomic analysis forms a potent engine that may find the correlation between plant structure, physiology, and biochemistry in scale. This is non-destructive non-phenotypic, sensor-based systems that are automated. In the field this is done through UAVs or ground rovers with multi-sensor arrays: RGB cameras to determine morphology, multispectral/ hyperspectral sensors to determine physiology and biochemistry, LiDAR to obtain 3D structure, and thermal cameras to detect stress. Controlled environments have conveyor-based systems which have fixed sensors to carry out similar functions. The result is a product of terabytes of geotagged images and spectral data of the phenotype (the observed characteristics) of all the plants or plots. The important connection is making a chemometric bridge. A representative tissue sample is determined among the HTP-screened population using spectral signatures. These are subjected to stringent metabolomic profiling with such methods as Liquid chromatography-Mass Spectrometry (LC-MS) or Gas chromatography-Mass Spectrometry

(GC-MS). This gives a detailed, quantitative picture of hundreds or thousands of primary and secondary metabolites -the biochemical phenotype. The high-dimensional data (spectra, images) of phenotypes is convoluted with the high-dimensional data (metabolite concentrations) of biochemistry. Models are trained using advanced machine learning (e.g. deep convolutional neural networks with image data, partial least squares discriminant analysis with spectral data). The goal is to find out what spectral bands or vegetation indices or image identifiers are predictive of certain, useful metabolites. Trained and verified, these models can be used to forecast the concentration of every metabolite in the field only using the spectral/image signature of that individual plant, in effect, producing a real time, spatially explicit map of the metabolome. One of the layers is the HTP-metabolomics connection. The entire strength comes out of committing multi-omics information into the spatial and temporal framework outlined by PA to generate a multi-scale interpretation of the genotype-to-phenotype spectrum. PA gives the geospatial container- the where and when. In this container, deposited is stratified biological information: The genetic blueprint (DNA sequence) of the cultivars being cultured, usually by genotyping-by-sequencing. Gene expression of plants in various management zones or receiving various treatments of precision elicitation, and how to identify which of the biosynthetic pathways is active.

This combination enables scientists and agronomists to transcend of correlation to mechanistic knowledge. To illustrate, studying plants in a high-polyphenol area, it is possible to observe not only increased polyphenols (metabolomics), but also the increased expression of phenylalanine ammonia-lyase (PAL) and chalcone synthase (transcriptomics) genes in the given environmental conditions (soil moisture, light exposure) recorded by the PA sensors. This allows the precision horticulture intervention (e.g., a certain light treatment) to be designed that is known to trigger the transcriptional cascade to produce the desired metabolite. This structure enhances the breeding of the molecules. Using the correlation of spatial yield and metabolite data with genomic markers, breeders are able to recognize Quantitative Trait Loci (QTLs) or genes linked to high biochemical functioning in real-world and variable settings. This results into cultivars that are specifically bred with stability and responsiveness in precise management systems. The final target is the multi-objective optimization. This needs advanced modeling with the ability to predict the usually competing results of biomass build up and secondary metabolite synthesis under varying management conditions. Two complementary methods are employed. Crop models (process-based e.g. modified versions of APSIM or DSSAT) have secondary metabolism sub-models added. These models employ physiological principles that model the partitioning of water, nitrogen and light into the growth and defense pathways. They are effective in investigating possible scenarios of what-if (e.g., what will happen when there is a 20% water deficit at flowering to anthocyanin yield?). Machine learning models (e.g., random forest, gradient boosting) are data-driven and are trained based on historical and real-time data of the digital pipeline. They obtain non-linear, intricate correlations between sensor inputs, management interventions and the two outputs of biomass and bioactive concentration. When these models are combined with real-time data streams, this results in the idea of a so-called digital twin of a field or greenhouse. The sensor data is constantly updated in this virtual replica. Simulations with this twin may be performed by the grower or by an AI agent: What will be the predicted effect of this nutrient recipe implemented with VRT in Zone A and this water deficit in Zone B on total dry yield and total flavonoid yield per hectare? The model gives optimum prescription maps that trade off goals, possibly 5 percent bio-mass in order to increase bioactive potency by 25 percent, based on priorities in the market. The prescriptive maps, created as a result of the digital pipeline, are senseless without the technological tool, which can implement them with accuracy. The next frontier is to go beyond bulk application to specific, effective and smart systems of delivery of the inputs that control plant health and direct metabolism. Mobilisation of elicitors (e.g., jasmonic acid, chitosan, salicylic acid) to enhance secondary metabolites is not very efficient because it can be degraded, lost by runoff and taken up non-specifically. Nanotechnology provides radical mode of delivery. Elicitors may be entrapped in or conjugated to nano-scaffolds like polymeric nanoparticles (e.g., chitosan, alginate), liposomes or silica nanoparticles. These carriers are designed to possess certain properties. Various advantages of this nano-encapsulation can be used in the management of bioactive in[61] Coats the elicitor to prevent early degradation by sunlight or microbes. Controlled Release: This is used to release the elicitor over time in a slow sustained manner that gives the induction signal a long-term and not transient signal. The nanoparticles can be structured to enhance easier entry via stomata or the cuticle and can be systemically translocated in the plant. In the future, surface functionalization of nanoparticles with specific ligands may enable the targeted delivery of nanoparticles to specific tissues of plants (e.g. glandular trichomes where essential oils are stored).

The use of nano-elicitor is made a precision tool. The multispectral scan of a zone using a UAV reveals a low terpenoid zone. The prescription map is created and a sprayer having VRT and possibly even nozzle level control dispenses a nano-elicitor formulation to that particular zone only.[62,63] This results in reduced doses, which are less expensive and with less environmental burden compared to more potent and localized biochemical response and is more efficient. The principles of VRT and sensing are currently being applied to the biological inputs which are key to the sustainable production of bioactive ingredients of high-quality and free of residues. The need of intervention is mapped with the use of PA technologies. Hyperspectral imaging is able to measure the initial phases of fungal disease (when it is not visible) based on slight variations in leaf reflectance. Machine vision cameras can recognize species and locations of weeds. In the same way, areas with low plant vitality (based on NDVI maps) may be identified and marked as biostimulant supported. Precision Application Technologies: In the case of biocontrol, this refers to the application of beneficial insects, fungi or bacteria to the exact location of pest or disease occurrence.[64,65] UAVs have the capability of dropping predatory mite sachets on individual hotspots. Sprayers can apply fungal biocontrol agents (i.e. Trichoderma) or bacterial agents (i.e. Bacillus thuringiensis) to only infected places, leaving beneficial insects elsewhere. In the case of biostimulants (e.g., seaweed extracts, humic substances, beneficial microorganisms such as plant growth promoting rhizobacteria),[66] VRT sprayers or in-line fertilizers can spray the products onto zones which the sensor data indicates are experiencing stress or low vitality. This enhances plant defense and secondary metabolism of the stressed regions homogenizing the quality of fields and limiting the transmission of stress signals that could have an impact on the surrounding plants. Dynamic Driving. The state of the art systems are closed-loop. As an instance, a system of pheromone traps and automated insect counters or spore traps with DNA-based detection of any pathogen can deliver real time pest/pressure information. This information gets directly to the decision system, which automatically causes a precision spray application of a biocontrol agent to occur only when an economic threshold is exceeded within a given geo-located block.

Challenges and future perspectives

Despite its transformative potential, the synergistic integration of precision agriculture, horticulture, and bioactive ingredient optimization faces significant multi-dimensional hurdles. Acknowledging these challenges is crucial for directing research, investment, and policy. Simultaneously, mapping clear future pathways is essential to translate this promising paradigm from experimental plots and controlled environments into widespread, commercially viable, and sustainable practice.

Table 3: Key challenges and future research directions for the integrated framework

Challenge Category	Specific Hurdles	Future Research & Innovation Directions
Technical & Analytical	High cost/complexity of sensor-metabolomics platforms; data fusion & interoperability issues.	Develop low-cost, real-time phytochemical sensors; establish open data standards and APIs.
Biological & Agronomic	Complex GxExM interactions; managing yield-quality trade-offs.	Build large-scale multi-location datasets; advance AI for multi-objective optimization.
Technological Delivery	Inefficient delivery and degradation of elicitors; non-targeted application.	Engineer nano-delivery systems for protected, controlled release of elicitors.
Systemic Integration	Disconnect from broader bioeconomy; energy footprint of high-tech systems.	Integrate with circular bioeconomy models (waste-to-value); conduct full Lifecycle Assessments (LCA).
Policy & Adoption	Gap between agri-tech and nutraceutical industries; need for skilled labor.	Foster public-private consortia; create certification standards; revolutionize agricultural education.

Technical and analytical hurdles

The sophistication of technology that makes such integration possible is also the main problem that prevents its adoption as there are issues of cost, complication, and data management. The pipeline which is at the basis of spectral sensing connecting to metabolomic validation is costly. The high-resolution hyperspectral sensors and UAVs such as the requirement to carry them are a significant capital expenditure that many small and medium-scale producers can not afford, yet many specialty crops that grow best under this method are of high value. Moreover, metabolomic ground-truthing necessary to construct strong calibration models entails the costly, destructive laboratory measurements with high-performance technologies in use (LC-MS/GC-MS) and professional skills.[67,68] This presents a Catch-22, in that strong models are required to justify the sensor investment, but the cost of constructing those models is too high without infrastructure in place to support it. The digital literacy and technical infrastructure required to manage armies of robots, drones, and sensor networks, as well as process terabytes of multi-modal data, is currently a high requirement which is often lacking in most of the agricultural areas. The interoperating system produces heterogeneous streams of data: spectral imagery, soil sensor records, weather records, genomic sequence, transcriptomic profile, and metabolomic records. Each stream may usually exist in proprietary formats in different spatial and temporal scales. To be able to integrate these into a coherent, analyzable entity is a mammoth informatics task. Universal data standards of agricultural biochemical phenotyping are in dire need. What is the geotag method of the metabolomic profile of a specific plant pixel in a UAV image? To what extent are data on terpenoid expression of a greenhouse trial interoperable with field data of another sensor brand? Lack of standard ontologies and Open Application Programming Interfaces (APIs) results in data silos, which impedes the creation of universal AI models and slows the progress of science due to low data sharability and reproducibility. In addition to the hardware and software, there are deep-seated challenges presented in the nature of plant biology and agricultural systems. The most typical demonstration of GxExM is the production of bioactive compounds. A cultivar (G) might react to a lack of water (M1) at a cool climate (E1), but have a different reaction to the same lack of water (M2) at a hot climate (E2). Such a three-way interaction is incredibly more complicated than the GxE interactions that are handled in the traditional yield-based PA. Creation of predictive models needs huge, multi-location, multi-year data which vary systematically across management inputs between genotypes in different environments. Prescriptions that are universally applicable are hard to make because of the combinatorial explosion of the number of possible scenarios. An AI model trained based on data of a herb farm in the Mediterranean will fail disastrously in a temperate climate without substantial recalibration, requiring localized model training that once more increases the cost and complexity requirements. The agronomic issue of central interest is the negative correlation between primary (growth, biomass yield) and secondary metabolism (production of bioactive compounds) most of the time. Stressing fruit with water can shrink fruit; nutrient limitation enhances alkaloid growth can retard the growth of plants. The multi-objective optimization models above are necessarily required, yet they have to deal with this inherent biological trade-off.[69,70] The economic optimum may not be always the biochemical or biophysical maximum. The difficulty lies in determining which level of management stress is the sweet spot, usually a mild and focused stress at a particular phenological stage, that will lead to the maximum economic value of the crop which is a combination of the volume of biomass and the concentration of desirable ingredients in that biomass. This value proposition has to be defined and communicated to the growers who are conventionally paid by weight, which is a big challenge.

RESULT AND DISCUSSION

To handle these challenges, it is necessary to conduct research and development efforts in a number of areas that are critical. The future will be in the transfer of indirect spectral prediction into direct low cost sensing. Two major studies are miniaturization and field deployable analytical devices. This includes advancements. Creating rugged, inexpensive, handheld or attached to simple robots hyperspectral or Raman spectrometers. Producing synthetic biosensors or nanoparticle-based probes that would be capable of binding to a class of compounds (e.g., flavonoids) and produce an optical or electrical signal which can be read by a rudimentary device. Chemical sensor arrays capable of profiling volatile organic compound imprints which are commonly direct measures of certain metabolic conditions and bioactive profiles allowing real-time measurement of crop biochemical condition. The new generation AI should grow to be more prescriptive and adaptive rather than merely predictive. Among the key directions are: Replacing black-box models that make predictions with models that can make inferences on causal relationship as part of the GxExM framework, and why a particular treatment did increase a compound. This creates trust and biological awareness. Applying the RL algorithms which provide the system with an opportunity to acquire the best management strategy, which is more likely to promote joint interaction of the system with the crop in a greenhouse or field, dynamically adapting the inputs to the most efficient use of resources and a combined rewarding function comprising the yield, bioactive content and resource use efficiency. Creating new, site-specific elicitation protocols or even new, harmless biostimulant molecules designed using AI to respond to genomic and metabolomic information to produce the desired pathway. The final sustainability examination of this triad is to test it by incorporating it into larger systems. The research should aim at Selecting PA to sort out the plant biomass that contains a specific high concentration of bioactives that cannot be sold in the main market (e.g. misshapen fruit, pruning residues) to extract efficiently in decentralised biorefineries to generate additional sources of revenue and avoid waste. Application of the blockchain technology in order to trace the biochemical profile of a batch within a particular zone of management during the processing stage to the end product (nutraceutical, functional food). This certifies high quality, transparency and may result in more equitable distribution of values to the grower who invested in quality improving practices. Implementing thorough LCAs to measure the actual environmental footprint of such high-tech systems, so that water and nutrient use efficiency gains do not lead to the expenditure of the embodied energy of sensor construction and data processing, and to implement the development of truly sustainable protocols.

CONCLUSION

It has achieved a well-purposed vision of high-value plant production in the future: the synergistic combination of Precision Agriculture, Advanced Horticulture, and Bioactive Ingredient Optimization. This synergy is iterative and mechanical. Precision Agriculture offers high-resolution spatial and temporal data canvas, which is spectral sensing to map the diversity of plant physiology and phytochemical content. Precision Horticulture uses this map to deliver dose-specific elicitors-whether in the form of water deficits, spectrally selective light or nano-encapsulated signaling molecules-to influence actively the production of plant secondary metabolism. The resulting Bioactive Ingredients, in turn, provide the direct biomarkers of the plant status, as the PA algorithms are refined and provide a valuable trait to breeding programs based on the high-throughput, field-based phenotyping. Results of vineyards maximizing polyphenols, regulated conditions to achieve optimal light to certain antioxidants and studies that combine metabolomics and UAV sensing indicate that this triad has the potential to shift mass production into fine-tuning biochemical production. The future lies not in technological proliferation but in smart convergence and system thinking. It involves the de-silicing of disciplinary boundaries between agronomists, plant physiologists, data scientists and chemists. The goal is the creation of “Phytochemically-Optimized Production Systems"-closed-loop, adaptive agricultural systems which address the biochemical profile of the crop as a primary, controllable output. These systems will, by implication, have AI-controlled virtual twins that continually simulate results, autonomous machines controlled by prescriptive maps, and passports protected by blockchain that contain the provenance and potency information of each batch, to an ever-increasing skeptical market. The maximization of tonnes per hectare is replaced by the maximization of nutritional or therapeutic value per unit of resource input a paradigm that is consistent with the pressing demands of both planetary and human health.

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Conflict of interest

The author declare that we have no conflict of interest.

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