An Integrated Biophysical and Engineering Study Linking Artificial Mechanical Stimulation and Subsurface Evaporation Dynamics with Water and Osmotic Transport Mechanisms for Improving Fruit Quality

Conceptual and Physical Framework of the Integrated System

This agricultural engineering study proposes an interdisciplinary scientific framework integrating soil thermodynamics, plant biophysics, and mechanical engineering principles to develop an innovative operational model aimed at enhancing internal water and nutrient transport and promoting the accumulation of micronutrients in fruits, thereby improving crop quality and market value.

The proposed concept is based on the synergistic coupling of two engineered physical stimuli:

1. **Thermally induced subsurface evaporation**, generated through a geometrically distributed network of micro-pits or subsurface wells surrounding the root zone. The number, depth, and spatial arrangement of these structures are adjusted according to atmospheric temperature, soil type, and hydraulic characteristics. This approach is hypothesized to modify moisture distribution, soil aeration, and thermal gradients within the rhizosphere.

2. **Artificial mechanical stimulation of plants**, achieved through low-intensity and low-frequency oscillatory motion generated by electrically driven actuators and flexible tension systems, with the objective of inducing beneficial biomechanical responses in plant tissues.

The integrated model hypothesizes that the interaction between these two stimuli may improve the efficiency of the Soil–Plant–Atmosphere Continuum (SPAC) by increasing transpiration-driven water flow and altering water potential gradients, thereby facilitating the transport of mineral nutrients and potentially improving the uptake and accumulation of selected macro- and micronutrients.

Furthermore, controlled mechanical stimulation may activate the phenomenon of **thigmomorphogenesis**, resulting in structural and physiological adaptations that could influence hydraulic conductivity, stomatal behavior, gas exchange efficiency, and the mechanical properties of stems and branches.

Main Scientific Hypothesis

The integration of:

- geometrically engineered soil modifications,
- controlled subsurface evaporation and aeration dynamics, and
- artificial mechanical stimulation of plants,

may contribute to:

1. Enhancing soil-to-plant water transport;
2. Improving the uptake efficiency of certain mineral nutrients and micronutrients;
3. Increasing water and nutrient use efficiency;
4. Improving fruit quality in terms of size, mineral composition, and physicochemical characteristics;
5. Developing a novel engineering approach applicable to organic agriculture and high-efficiency water management systems.

Given the multifactorial nature of the proposed system, experimental and field-scale investigations are required to validate these hypotheses, quantify the magnitude of the effects, and determine the optimal operating conditions under different environmental and agronomic scenarios.

Soil Thermodynamics and Subsurface Evaporation through Engineered Wells

The physical and thermal properties of soil govern the partitioning of incoming solar radiation into the various components of energy flux within the soil–atmosphere system. Soil temperature, moisture content, porosity, and thermal conductivity are among the primary factors controlling heat and water transport within the root zone.

The energy balance at the soil surface is commonly described by the classical surface energy balance equation:

$$R_n = H + LE + G$$

where:

- R_n is the net radiation at the soil surface (W m^{-2});
- H is the sensible heat flux to the atmosphere (W m^{-2});
- LE is the latent heat flux associated with evaporation and transpiration processes (W m^{-2});
- G is the soil heat flux (W m^{-2}).

Within the proposed system, geometrically distributed engineered wells or micro-pits surrounding the root zone are hypothesized to modify the components of this energy balance by increasing the effective heat exchange surface, improving soil aeration, and generating localized thermal and moisture gradients within the soil profile.

From a theoretical perspective, these modifications may enhance subsurface evaporation and promote capillary water movement toward the rhizosphere, potentially increasing water flux within the Soil–Plant–Atmosphere Continuum (SPAC). Furthermore, the proposed structures may alter the effective hydraulic properties of the soil and influence the spatial distribution of moisture and temperature around the root system.

Consequently, the engineered wells can be regarded as thermo-hydraulic control structures capable of redistributing energy and water fluxes within the soil environment. Their actual effectiveness, however, requires rigorous experimental characterization and mathematical modeling under diverse climatic and agronomic conditions.

Soil Thermodynamics and Subsurface Evaporation through Engineered Wells

Under natural conditions in bare soils, active evaporation is generally confined to a very shallow near-surface zone. As drying progresses following rainfall or irrigation events, the evaporation front gradually recedes into the soil profile, reducing liquid water transport through capillary flow and causing moisture transfer to become increasingly dominated by vapor diffusion, which is generally a less efficient transport mechanism.

The present study proposes the introduction of a network of engineered vertical wells or pits surrounding trees, with depths ranging approximately from 0.5 to 1.2 m and diameters between 100 and 150 mm. These dimensions may be adjusted according to soil characteristics, climatic conditions, and crop requirements.

From a theoretical perspective, these engineered structures may function as additional pathways for heat and mass exchange between the soil surface and deeper regions of the rhizosphere. Consequently, they may alter soil heat fluxes and increase the spatial heterogeneity of temperature and moisture distributions within the soil profile.

It is hypothesized that such conditions could promote the development of coupled thermo-hydraulic transport zones within the unsaturated porous medium. Liquid water may evaporate near the warmer pit walls, while water vapor migrates under gradients of vapor pressure and temperature and subsequently condenses in cooler regions, releasing latent heat and contributing to the redistribution of energy and moisture within the soil.

If experimentally validated, these engineered wells could represent a thermo-hydraulic control system capable of modifying soil water and energy dynamics in the root zone and, indirectly, influencing water uptake efficiency and nutrient transport within the plant.

Soil Thermodynamics and Subsurface Evaporation through Engineered Wells

Under natural conditions in bare soils, active evaporation is confined to a shallow near-surface layer. As soil drying progresses following rainfall or irrigation, the evaporation front gradually recedes into the soil profile, reducing liquid water transport and causing moisture movement to become increasingly dominated by vapor diffusion.

The introduction of a network of engineered vertical wells or pits around trees, with depths ranging from 0.5 to 1.2 m and diameters between 100 and 150 mm, is hypothesized to alter heat and moisture transport dynamics within the rhizosphere. These structures may act as additional pathways for heat and mass exchange, thereby modifying soil heat fluxes and increasing local thermal and moisture gradients.

Theoretically, such conditions may promote the development of coupled thermo-hydraulic convective cells within the unsaturated porous medium, where liquid water evaporates near warmer pit walls and water vapor migrates along vapor-pressure and temperature gradients before condensing in cooler regions, releasing latent heat and redistributing energy and moisture within the root zone.

The proposed system is hypothesized to improve plant physiological performance by enhancing water dynamics, root-zone aeration, and nutrient transport, thereby potentially increasing plant tolerance to certain biotic stresses and reducing susceptibility to agricultural pests. The implementation of this approach relies primarily on managed irrigation systems, as a continuous and controlled water supply is required to maintain the thermal and moisture gradients necessary for system operation. In contrast, natural rainfall alone is generally insufficient to sustain these processes under most agricultural conditions.

Biophysical Basis of Water Potential and Osmotic Regulation in Plants

Water transport within plants occurs through a continuous hydraulic continuum known as the Soil–Plant–Atmosphere System, extending from the soil solution to the atmosphere via xylem vessels. This movement is driven by gradients in water potential (❧\psi_w❧).

The flow is governed by the cohesion–tension mechanism, where transpiration-induced water loss from leaves generates negative pressure within the xylem, pulling water upward along a gradient from higher to lower water potential.

The total plant water potential is expressed as:

[\psi_w = \psi_s + \psi_p + \psi_g]

where:

- ψ_w: total water potential
- ψ_s: solute (osmotic) potential
- ψ_p: pressure potential
- ψ_g: gravitational potential

Principles in Plant Physiology indicate that root water uptake is directly controlled by the gradient between soil water potential and root water potential, which is influenced by solute concentration, soil salinity, and membrane transport activity.

Osmotic regulation plays a central role in water entry into root cells, where water moves across semipermeable membranes from regions of higher to lower water potential, contributing to root pressure formation and supporting upward hydraulic transport within the xylem network.

A decrease in soil moisture leads to a reduction in plant water potential, which in turn triggers an increase in abscisic acid (ABA) accumulation within the xylem sap. ABA acts as a primary hormonal signal regulating drought response, particularly by inducing stomatal closure to minimize hydraulic water loss.

The osmotic properties of guard cells play a central role in regulating stomatal aperture. During periods of active transpiration, water is lost from the guard cell walls, leading to an increased concentration of apoplastic solutes within the cell wall environment.

Sucrose concentrations in the apoplast may rise during peak daytime conditions to approximately 150 mM, generating a negative osmotic potential that draws water out of guard cells, reduces turgor pressure, and ultimately leads to stomatal closure. This process helps limit water loss and reduces the risk of xylem embolism.

Dynamic Comparison: Wind versus Artificial Mechanical Stimulation

Natural wind movement and artificial mechanical vibration influence plants through distinct biophysical pathways, depending on boundary layer characteristics, airflow intensity, and the activation of mechanical and hormonal signaling networks. Wind represents a stochastic and environmentally variable stimulus, whereas artificial mechanical stimulation provides a controlled, periodic input that can be precisely tuned in intensity and frequency, leading to more predictable physiological responses.

Historical and modern studies indicate the existence of an optimal wind speed for plant growth of approximately $1 \, \text{m/s}$, as reported in Wadsworth (1959). Growth rates decline when wind speed exceeds or falls below this threshold. The primary limitation of strong natural wind is its tendency to induce excessive transpiration, which may lead to severe water stress or hydraulic failure in plants.

In contrast, the use of mechanical agitators allows direct transmission of vibrational energy into the plant structure without relying on desiccating airflow. This enables the simulation of the beneficial structural effects of wind while minimizing associated hydraulic stress.

Direct mechanical stimulation induces repeated elastic deformation in plant tissues, activating mechanoreceptors and triggering pressure-sensitive calcium channels. This initiates ionic signaling cascades that modify the internal hormonal balance. Consequently, elevated levels of ethylene and jasmonic acid promote cell wall remodeling, increased xylem structural reinforcement, and enhanced mechanical strength without compromising overall hydraulic conductivity.

Mechanical vibration also enhances internal defense mechanisms. Activities of antioxidant enzymes such as superoxide dismutase (SOD) and ascorbate peroxidase (APX) increase, while levels of reactive oxygen species and lipid peroxidation markers such as hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) decrease, improving membrane stability and overall plant stress tolerance.

Micronutrient Enrichment and Fruit Quality Enhancement

The transport of mineral nutrients and micronutrients from soil to fruits represents a major limitation in agricultural physiology. Elements such as calcium (Ca), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are either phloem-immobile or poorly mobile, and their transport depends primarily on the xylem-driven transpiration stream.

As fruits mature, xylem inflow gradually declines, limiting the accumulation of these nutrients and contributing to physiological disorders and reduced nutritional quality.

The proposed integrated system (subsurface evaporation via engineered pits combined with mechanical stimulation) functions as a quasi-biophysical pumping mechanism. Vertical pits enhance local solute concentration in the rhizosphere through controlled evaporation, while mechanical vibration reduces leaf boundary layer resistance and strengthens transpiration pull, thereby sustaining continuous xylem-mediated transport of minerals toward developing leaves and fruits.

1. Heat Flux and Evaporation Calculations in Soil and Vertical Wells

The soil heat flux density (G) at the surface and within the soil profile can be estimated using the finite-difference approach coupled with soil heat storage:

$$G = G_{z} + C_s \int_{0}^{z} \frac{\partial T}{\partial t} \, dz$$

where G_{z} is the measured heat flux at depth z, and C_s is the volumetric heat capacity of soil, estimated according to the de Vries model:

$$C_s = \rho_m C_m \chi_m + \rho_w C_w \theta$$

For dry mineral soils, a reference value of:

$$C_s = 1.919 \times 10^6 ; \text{J m}^{-3}\text{K}^{-1}$$

is commonly adopted.

Subsurface evaporation at the walls of engineered wells may be described through the latent heat balance:

$$E_{\text{sub}}=-\frac{1}{L\rho_w}\nabla \cdot \mathbf{q}_v$$

where the vapor flux is given by:

$$\mathbf{q}_v=-D_v c_v' \nabla h-D_v h s \nabla T$$

The proposed framework hypothesizes that strong thermal gradients within the wells may enhance coupled heat and mass transfer and promote localized evaporation near the rhizosphere.

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2. Aerodynamic Resistance of Leaves and the Effect of Mechanical Vibration

The aerodynamic resistance of the leaf boundary layer (r_a) is estimated using the Penman–Monteith formulation:

$$r_a=\frac{\ln\left(\frac{z_m-d}{z_{om}}\right)\ln\left(\frac{z_h-d}{z_{oh}}\right)}{k^2u_2} \approx \frac{208}{u_2}$$

where u_2 is the wind speed at a height of 2 m and

$$k=0.41$$

is the von Kármán constant.

Under mechanically induced oscillation, heat and mass transfer can be characterized by the vibrational Reynolds number:

$$VRe=\frac{2\pi fad}{\nu}$$

and the modified Nusselt number:

$$Nu_{\text{vib}}=C(VRe)^mPr^n$$

where:

$$Pr \approx 0.71$$

is the Prandtl number of air and ν is the kinematic viscosity.

Theoretically, vibration may reduce boundary layer thickness and enhance heat and mass exchange around leaf surfaces.

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3. Vibration Mechanics and Safe Mechanical Stress in Trees

Leaves and branches may be modeled as damped harmonic oscillators governed by:

$$m\frac{d^2x}{dt^2}+c\frac{dx}{dt}+k_ex=F(t)$$

where:

- m is the equivalent mass,
- c is the damping coefficient,
- k_e is the tissue stiffness.

Tissue stiffness is strongly associated with cellular turgor and hydration status; therefore, the vibrational characteristics of plant tissues may vary under different levels of water stress.

The maximum vibrational acceleration is given by:

$$a_{\text{max}}=(2\pi f)^2 a$$

To ensure plant safety, vibration frequency and amplitude should remain within experimentally validated operating limits that stimulate beneficial mechanobiological responses without causing structural damage or excessive mechanical stress.

Engineering Layouts and Applied Design Components of the Proposed System

Layout I: Vertical Configuration of Thermal Wells and Subsurface Evaporation

The proposed design employs a circular array of engineered vertical wells distributed around the tree canopy projection to ensure homogeneous coverage of the active rhizosphere. The system consists of four to six wells per tree, with operational depths ranging from 0.5 to 1.2 m and diameters between 100 and 150 mm.

The wells are lined with perforated porous sleeves and geotextile filters to prevent soil particle intrusion while maintaining heat and gas permeability. These structures are hypothesized to function as vertical pathways for heat and moisture transport, thereby enhancing energy redistribution, soil aeration, and thermo-hydraulic exchange within the root zone.

Layout II: Mechanical Vibration and Physiological Control Unit

The mechanical module consists of a programmable vibration actuator attached to the trunk or major branches using a flexible shock-absorbing collar to ensure uniform transmission of mechanical energy.

The system is designed to generate periodic oscillations within predetermined frequency and amplitude ranges according to plant species and developmental stage. The objective is to stimulate beneficial mechanobiological responses, reduce leaf boundary-layer resistance, and enhance transpiration and hydraulic transport while avoiding excessive mechanical stress.

Layout III: Integrated Physico-Chemical Feedback System

The thermal wells and vibration unit operate as an integrated Soil–Plant–Atmosphere Continuum (SPAC) system, in which soil heat and moisture dynamics interact with mechanical stimulation of the canopy to enhance water and mineral transport throughout the plant.

This integrated framework is hypothesized to improve the transport of poorly mobile nutrients, including calcium, iron, zinc, and manganese, toward developing tissues and fruits while increasing water-use efficiency and overall physiological performance.

Conclusions and Investment Recommendations

The proposed conceptual and theoretical framework suggests that coupling soil thermal engineering with controlled mechanical stimulation of trees may provide an innovative approach for improving water-use efficiency, enhancing micronutrient transport, and increasing the quality and productivity of horticultural crops.

From an applied perspective, the system could be developed into an intelligent agricultural technology comprising low-energy mechanical vibration modules, engineered thermal wells, and integrated sensing and control platforms.

The study recommends conducting multi-site field experiments and advanced numerical modeling to validate the proposed hypotheses and determine optimal operating conditions before proceeding toward intellectual property protection, commercial development, and large-scale agricultural implementation.