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QUANTUM-RESONANT ENERGY COUPLING IN AGRICULTURE (QREC-AGRI): A FALSIFIABLE MULTISCALE FRAMEWORK FOR TESTING NON-CONTACT EFFECTS IN PLANT-SOIL-WATER SYSTEMS

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ABSTRACT

Agriculture increasingly requires interventions that improve yield stability, resource-use efficiency and stress resilience without proportionally increasing chemical or energetic inputs. Quantum-Resonant Energy Coupling for Agriculture (QREC-Agri) is a proposed remote, non-contact intervention whose initiating physical mechanism is presently unresolved. Rather than infer mechanism from outcome, this article develops a falsifiable framework that separates four evidentiary layers: agronomic efficacy, biological mediation, physical coupling and quantum-mechanistic attribution. At the efficacy stage, QREC-Agri is treated as a black-box randomised intervention with auditable assignment and timing. Candidate biological responses are anchored to established plant processes, including photosynthetic excitation and electron transfer, proton-coupled electron transfer, enzyme-catalysed hydrogen transfer, radical-pair chemistry, membrane and aquaporin transport, electrical/Ca^{2+} /reactive-oxygen signalling and rhizosphere-mediated nutrient acquisition. We formalise competing null, classical-pathway, unresolved-coupling and mechanism-specific hypotheses; derive prospective pathway-level predictions and falsifiers; define a causal estimand; and specify safeguards against pseudoreplication, spatial interference, selective reporting and post hoc configuration changes. The validation architecture requires pre-registration, sham assignment, blinded outcome assessment, treatment-fidelity auditing, independent replication, equivalence testing against a smallest agronomically meaningful effect and, for mechanism claims, a prospectively specified physical observable that discriminates competing models. The framework is intentionally asymmetric: positive phenotypes may justify further study, but quantum attribution is permitted only after reproducible efficacy, biological pathway localisation, exclusion or modelling of sufficient classical explanations and direct mechanism-specific evidence. Although developed around QREC-Agri, the framework is generalisable to remote or non-contact biological interventions for which exposure metrology is incomplete. Its purpose is to convert an unconventional technology proposition into a sequence of experiments capable of confirmation, refinement or rejection.

Keywords: QREC-Agri; Quantum biology; Molecular resonance; Photosynthesis; Plant signalling; Rhizosphere; Non-contact intervention; Falsifiability; Plant phenotyping; Reproducibility.

1 INTRODUCTION

Agricultural production must deliver higher and more stable outputs under water scarcity, salinity, soil degradation, nutrient constraints, heat and increasingly variable weather. These pressures have accelerated interest in biological, digital and physical interventions that may improve crop performance without proportional increases in fertiliser, pesticide, water or energy inputs. Yet unconventional technologies often enter commercial testing before their mechanisms, boundary conditions and evidentiary standards are defined. That sequence creates a predictable problem: positive field observations can be difficult to interpret because spatial heterogeneity, microclimate, handling, pseudoreplication, regression to the mean and selective endpoint reporting can mimic a treatment effect.

QREC-Agri is the agricultural application of Quantum-Resonant Energy Coupling-Molecular Resonance Technology (QREC-MRT™), conceived as a remote, non-contact intervention directed to a defined biological or material target. The present article does not assume a known carrier, field, force or non-local mechanism. At the efficacy stage, QREC-Agri is therefore treated operationally as a black-box intervention with auditable assignment and timing. The working proposition is not that the intervention supplies the bulk energy required for plant growth. Plants remain powered by solar radiation, redox chemistry, electrochemical gradients and metabolism. Rather, if an effect exists, the hypothesis is that the intervention changes the probability, kinetics or regulatory state of one or more downstream biological processes, with endogenous metabolism providing the energy for any subsequent amplification.

Quantum biology offers a relevant but demanding conceptual context. All biological chemistry is ultimately quantum mechanical, but that fact alone does not classify a macroscopic plant response as a quantum effect. Contemporary reviews emphasise the need to distinguish generic quantum-mechanical chemistry from functionally relevant quantum phenomena in biology [1,2]. Coherence, tunnelling and spin dynamics are among the principal domains under investigation [3,4]. Their interpretation also requires careful discrimination from classical alternatives and attention to how microscopic effects could influence biological function [5]. This distinction is central to the present framework.

Accordingly, the paper addresses three sequential questions: (i) does QREC-Agri produce a reproducible, pre-specified biological or agronomic effect under controlled conditions? (ii) if so, can conventional environmental, electromagnetic, thermal, chemical, statistical or behavioural explanations account for the effect? and (iii) only if those explanations are insufficient, is there a mechanism-specific physical observable capable of discriminating among competing models? This sequence makes the technology empirically testable without requiring evaluators to accept its proposed physics in advance.

The conceptual contribution of this article is therefore not a claim that QREC-Agri has already been mechanistically explained. It is a demarcation framework that separates efficacy, biological mediation, physical coupling and quantum attribution; maps each level to prospective measurements; and specifies the evidence required to move from one level to the next.

1.1 Scientific contribution and testable commitments

The framework makes five commitments that distinguish a scientific test from a post hoc technology narrative. First, efficacy is defined by a pre-specified estimand and a practically meaningful effect threshold rather than by statistical significance alone. Second, treatment assignment is separated from mechanism: an effect of assignment can be estimated before the initiating exposure is physically characterised. Third, any proposed biological mediator must satisfy temporal ordering and cross-scale coherence. Fourth, a remote intervention must explicitly address interference between experimental units, because an effect that spills into controls can invalidate ordinary treatment-control comparisons. Fifth, null and negative results are informative outcomes that can reject or narrow the tested configuration.

These commitments convert QREC-Agri into a sequence of prospective tests rather than a retrospective explanation. A claim may advance from efficacy to mechanism only when the evidence required at the preceding level has been met.

1.2 Research gap and generalisable contribution

The literature relevant to QREC-Agri is fragmented across quantum biology, plant electrophysiology, photosynthetic biophysics, water transport, rhizosphere ecology and experimental methodology. Those literatures establish candidate processes and measurement tools, but they do not provide an accepted inferential pathway for a remote intervention whose initiating exposure is not yet metrologised. The central gap is therefore methodological as much as mechanistic: how should evidence be staged so that a reproducible agronomic effect is neither dismissed because its mechanism is incomplete nor overinterpreted as proof of a quantum process?

This article addresses that gap by combining causal estimands, interference-aware field design, pathway-specific temporal predictions, mechanism-discriminating observables and explicit claim thresholds in one framework. The resulting architecture is intended to be generalisable to other remote, low-energy or non-contact biological interventions with incomplete exposure models.

2 SCOPE, DEFINITIONS AND SCIENTIFIC DEMARCATION

2.1 Operational definition of QREC-Agri

For research purposes, QREC-Agri is defined operationally as a pre-specified intervention applied to pre-identified experimental units for a recorded duration and schedule, using a proprietary configuration intended to address a defined target system. The scientific record must separate proprietary implementation from the metadata required for independent evaluation. At minimum, evaluators should know the allocation of treatment, sham and control units; target identifiers; start and stop times; intervention schedule; protocol deviations; and the primary endpoints and analysis plan fixed before unblinding.

The term 'molecular signature' should not be interpreted as a single frequency possessed by a whole plant. Molecules and molecular assemblies possess multiple rotational, vibrational, electronic and spin-dependent states, while living tissues display broad, environment-dependent spectra and collective dynamics. A generic operational descriptor can be written as:

$$S_T = \{f_i, A_i, \varphi_i, \tau_i, \ldots\},$$

where S_T denotes a schematic target-system descriptor, f_i characteristic spectral or dynamical components, A_i their weighting, φ_i relative phase relationships and τ_i relevant temporal parameters.

This notation is descriptive, not a validated physical exposure equation. In particular, it does not imply that these variables constitute a propagating field, that they uniquely specify the proprietary implementation, or that resonance has been experimentally demonstrated. In this paper, the term resonance is provisional and becomes a physical claim only if a reproducible parameter-response relation or other discriminating resonance signature is observed prospectively.

2.2 What the hypothesis does and does not claim

The principal scientific boundaries between permissible QREC-Agri working hypotheses and claims that would require additional evidence are summarised in Table 1.

Table 1: Scientific claim boundaries for QREC-Agri.

Claim domain	Permissible working statement	Claim not justified without new evidence
Energy	Any biological effect would be amplified by endogenous energy sources and metabolism.	QREC remotely supplies the metabolic energy embodied in increased biomass.
Resonance	A configured intervention may produce a reproducible state-dependent response.	A crop or organism has one unique resonance frequency.
Quantum biology	Quantum-sensitive processes exist in relevant biological chemistry.	The presence of quantum processes in cells proves QREC is quantum-mediated.
Entanglement	Entanglement may be discussed as a precise quantum concept and potential future test domain.	Remote correlation alone is evidence of entanglement.
Efficacy	A blinded, replicated treatment-control difference can support efficacy under tested conditions.	A single positive field observation establishes general efficacy or mechanism.

2.3 Physical agnosticism and conservation constraints

Because no public exposure model is established here, this framework does not infer a carrier, transmission pathway, entanglement process or non-local interaction from the term 'remote'. Any future physical model must make quantitative predictions and remain consistent with established conservation laws, thermodynamics and causal signal-propagation constraints. Until a measurable exposure observable is identified, efficacy trials should therefore be analysed exactly as black-box intervention studies. A positive phenotype can motivate mechanism research, but cannot by itself determine how the intervention acts.

2.4 Established physical lineage: resonance, quantisation and molecular-state dynamics

The physical ideas relevant to the QREC-Agri hypothesis are not novel in themselves. Resonance is a standard concept across classical and quantum physics: a system can respond preferentially when an external perturbation couples to one or more of its natural dynamical modes. At molecular scale, those modes are not represented by a single 'frequency of the organism' but by quantised rotational, vibrational, electronic and spin-dependent states, together with broadened and coupled transitions in condensed and biological matter [2,4]. Spectroscopic studies of photosynthetic systems illustrate how state-dependent interactions, coherent dynamics and energy transfer can be experimentally resolved [6,7]. Thus, spectral selectivity, state-dependent coupling and resonance are established organising concepts in physics and physical chemistry. What remains unestablished is whether the proprietary QREC configuration can reproducibly engage any such process under the remote treatment conditions proposed here.

The same distinction applies to quantum effects in biology. Proton-coupled electron transfer is an established component of biological energy conversion [8,9]. Quantum mechanical hydrogen tunnelling contributes to selected enzyme-catalysed reactions [10,11]. Excited-state and coherent dynamics have been examined extensively in photosynthetic complexes [6,12]. Spin-dependent radical-pair chemistry has likewise been investigated in cryptochrome systems [13,14]. Their presence in biology does not constitute evidence for QREC-Agri, but it establishes that biological function can depend on molecular processes whose rates, transition probabilities and state populations are described quantum mechanically. The scientific question for QREC-Agri is therefore not whether such physics exists, but whether the intervention produces a reproducible and specifically predicted perturbation of one or more of these processes.

A useful physical distinction is between energy delivery and state perturbation. In many established systems, a comparatively small perturbation can alter the probability or rate of a transition while the bulk energy that supports the eventual macroscopic response is drawn from the system itself. Catalysis, photochemical charge separation, ion-channel gating and biochemical signalling all illustrate this general principle, although they operate through different mechanisms. Accordingly, QREC-Agri should not be framed as remotely supplying the energy contained in additional biomass. If an effect is demonstrated, a more defensible physical question is whether the intervention changes a transition rate, coupling efficiency, population distribution or regulatory state that is subsequently amplified by photosynthesis, electrochemical gradients and metabolism.

This historical and physical continuity is important for interpretation. The constituent concepts of resonance, molecular quantisation, energy transfer and biological amplification are established science; the potentially novel claim lies in their proposed remote, target-specific implementation within QREC-MRT™. Novelty of application must therefore be kept separate from novelty of physical law. The present framework assumes no new law of physics and requires any future QREC-specific model to remain quantitatively compatible with known conservation laws, thermodynamics and causal constraints while generating predictions that distinguish it from conventional alternatives.

2.5 Formal competing hypotheses

The competing hypotheses used to distinguish null, classical, unresolved and mechanism-specific interpretations are summarised in Table 2.

Table 2: Competing hypotheses and evidentiary requirements for QREC-Agri.

Hypothesis	Statement	What would support it
H0: Null	Observed differences are attributable to ordinary biological, environmental and analytical variability.	No reproducible treatment-control effect under adequate power and protocol fidelity.
H1: Classical pathway	A reproducible effect exists and is explainable by measurable classical physical or environmental pathways.	Effect covaries with thermal, electromagnetic, chemical, handling or other measured classical variables.
H2: Biological response, physical origin unresolved	A reproducible response survives routine classical controls, but the initiating physical mechanism remains unidentified.	Independent efficacy plus coherent biological pathway evidence without a discriminating physical signature.
H3: Mechanism-specific physical model	A reproducible effect survives defined alternatives and displays a pre-specified observable that discriminates a specific physical model.	Independent replication of a model-specific spectroscopic, isotope, spin, phase/frequency or other discriminating signature.

2.6 Minimal causal model and primary estimand

At the efficacy stage, the experimentally identifiable quantity is the effect of treatment assignment, not the effect of an unmeasured physical exposure. Let Z denote randomised assignment (QREC-Agri, sham or control), E the effective initiating exposure or coupling state (currently latent), M an early biological mediator and Y the agronomic outcome. The minimal causal structure is Z → E → M → Y, with measured environmental and management variables C affecting M and Y. Randomisation can identify an intention-to-treat contrast in Y between assigned groups even while E remains unmeasured; it cannot by itself identify the physical mechanism represented by E.

Accordingly, the primary estimand for an efficacy trial should be defined prospectively as the between-group difference in the chosen agronomic endpoint at a specified time or over a specified interval, adjusted only for pre-declared baseline covariates. Mechanistic mediation analyses are secondary until an early mediator is measured reliably and shown to precede the outcome. This separation prevents a positive crop response from being overinterpreted as evidence for a particular coupling model.

The resulting causal sequence, from assigned intervention through candidate biological mediation to agronomic outcome, is summarised in Figure 1.

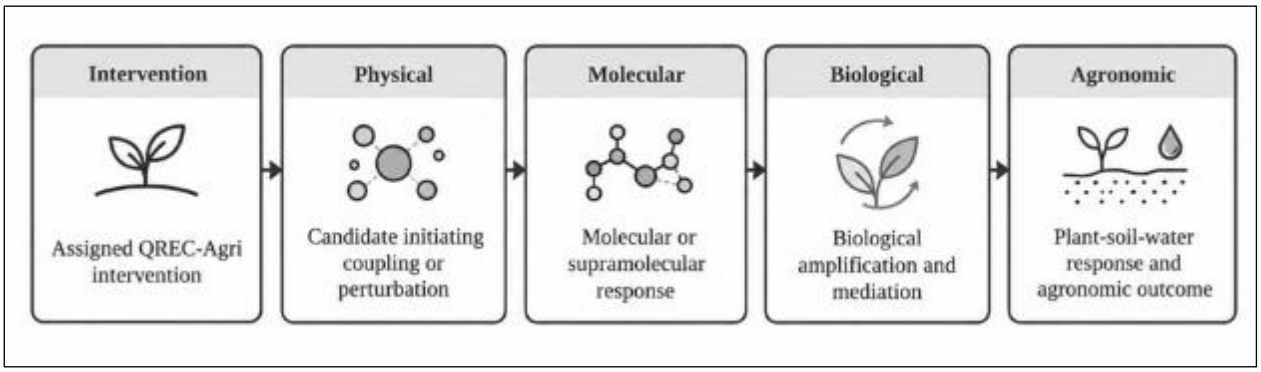


Figure 1: Proposed multiscale causal framework for QREC-Agri.

3 QUANTUM-BIOPHYSICAL CONTEXT RELEVANT TO THE HYPOTHESIS

The purpose of this section is not to use quantum terminology as an explanatory shortcut. It identifies established biological processes in which quantum mechanics or molecular-state dynamics are experimentally relevant and asks what observations would be needed to connect any QREC-Agri effect to those processes.

3.1 Photosynthetic excitation and electron transfer

Photosynthetic light harvesting is the clearest plant example of a molecular process in which electronically excited states, pigment-protein coupling and energy transfer can be investigated at ultrafast timescales. Early spectroscopy studies reported coherent dynamics in photosynthetic complexes [12,15]. Related work extended these observations to other light-harvesting systems and clarified their physical interpretation [6,16]. Subsequent work has shown that efficient energy transfer does not require long-lived electronic coherence and that vibrational and environmental contributions must be separated carefully [17]. The correct inference for QREC-Agri is therefore modest: photosynthetic systems contain measurable molecular states and transfer processes, but their existence does not validate an external resonant intervention.

If QREC-Agri influences photosynthetic energy conversion, that hypothesis generates temporal and directional predictions. Changes in chlorophyll fluorescence or gas exchange should precede, or at least accompany, changes in biomass and yield. Chlorophyll fluorescence provides established non-destructive measures such as Fv/Fm, operating efficiency of PSII (ΦPSII) and non-photochemical quenching [18,19]. Their interpretation under stress is well developed [20]. Electron transport and gas-exchange measurements provide complementary information on photosynthetic function and carbon assimilation [7,21]. A yield response in the absence of any corresponding photosynthetic signal would weaken a specifically photosynthetic mechanism while leaving alternative pathways open.

Figure 2 places these candidate measurements within the established photosynthetic energy-conversion chain without assigning QREC-Agri to any particular step.

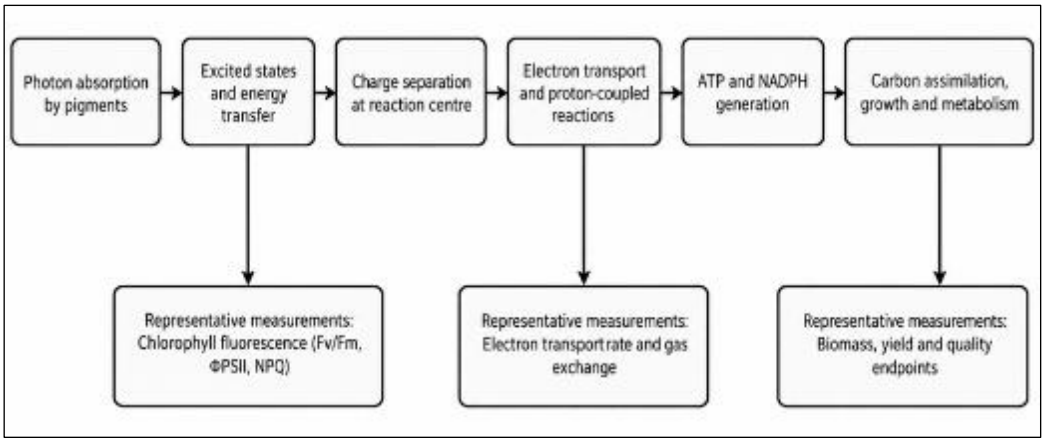


Figure 2: Established photosynthetic energy-conversion context.

3.2 Proton-coupled electron transfer and enzymatic hydrogen tunnelling

Proton-coupled electron transfer (PCET) is central to biological energy conversion, including photosynthetic redox chemistry [8,9]. Quantum mechanical tunnelling contributes to some enzyme-catalysed hydrogen-transfer reactions, with protein dynamics, electrostatics and vibrational gating influencing barrier properties [10,11]. These findings justify asking whether an intervention changes reaction kinetics in a quantum-sensitive biochemical system. They do not justify the stronger claim that QREC-Agri controls tunnelling. A mechanistic programme would require kinetic measurements, isotope-sensitive experiments or other observables capable of distinguishing alternative models.

3.3 Radical-pair chemistry and magnetic sensitivity

Spin-dependent radical-pair chemistry has been investigated in cryptochrome systems as a candidate mechanism for magnetic sensitivity [13,22]. Experimental studies have also highlighted reproducibility and interpretation challenges in plant magnetic responses [14,23]. This mixed literature is important because it shows why a field-responsive phenotype cannot be treated as self-interpreting. Exposure metrology, sham conditions, independent replication and model-discriminating observables are essential before invoking spin chemistry or any other quantum mechanism. These studies do not imply that QREC-Agri generates a conventional magnetic field or acts through cryptochrome; they define one experimentally mature example of how a quantum-sensitive biological mechanism can be tested.

The broader plant literature also reports physiological responses to applied magnetic fields under selected experimental conditions [24,25]. For example, static magnetic-field exposure has been associated with altered Arabidopsis root growth through auxin-related signalling [26]. These observations establish only that plants can respond to some conventional physical-field exposures; they do not establish that QREC-Agri uses a magnetic mechanism or that such effects extrapolate to remote QREC treatment.

3.4 Water, ions and membrane transport

Plant water relations depend on water potential gradients, xylem transport, stomatal regulation and membrane transport. Aquaporins facilitate water and selected small-molecule flux across membranes and are subject to dynamic regulation [27,28]. Their cellular expression, trafficking and functional control are linked to pH, phosphorylation and stress responses [29]. Aquaporins also contribute to coordinated water and CO_2 transport in leaves [30]. The phrase 'water restructuring' should therefore be avoided unless accompanied by direct and reproducible structural or spectroscopic evidence. A stronger formulation is that treatment may alter measurable water-ion behaviour or plant water transport. Candidate measurements include pH, electrical conductivity, oxidation-reduction potential, dissolved oxygen, surface tension, leaf water potential, stomatal conductance, transpiration and water-use efficiency. If a water-state mechanism is advanced, Raman, FTIR, NMR or related measurements should be specified prospectively.

4 CANDIDATE BIOLOGICAL AMPLIFICATION PATHWAYS

The four candidate biological response routes considered in this framework are summarised in Figure 3.

4.1 Photosynthetic pathway

A molecular-scale perturbation becomes agronomically relevant only if it propagates into measurable physiology. Photosynthesis is a high-gain candidate pathway because photon capture, charge separation, electron transport, proton

translocation, ATP/NADPH generation and carbon fixation are tightly coupled. A treatment-specific change should therefore be sought in pre-specified fluorescence and gas-exchange variables before or alongside growth responses.

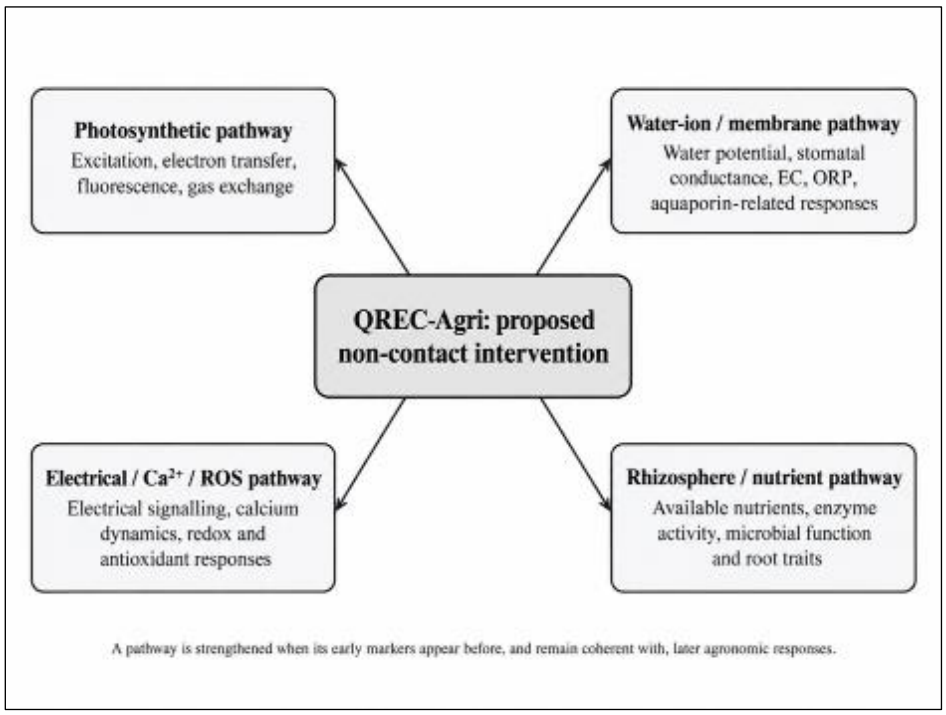


Figure 3: Candidate biological response pathways for QREC-Agri.

4.2 Water-ion and membrane-transport pathway

Water relations provide a second high-gain candidate pathway because small changes in hydraulic conductance, stomatal regulation or ion transport can propagate to photosynthesis, nutrient acquisition and growth. A prospective test should distinguish bulk-water properties from plant-mediated transport. Candidate endpoints include irrigation-normalised water use, soil and substrate water potential, leaf water potential, stomatal conductance, transpiration, pH, EC, oxidation-reduction potential and, where mechanistically justified, aquaporin abundance or phosphorylation state. Claims of altered water structure require direct spectroscopy and should not be inferred from conductivity or growth alone.

4.3 Electrical, Ca^{2+}, ROS and stress-signalling pathway

Plants transform local stimuli into systemic signals. Rapid long-distance electrical and calcium signalling is well established in plants [31,32]. Reactive oxygen species also function as regulated local and systemic signals during stress [33,34]. Integration between ROS and calcium signalling provides an additional amplification layer in abiotic stress responses [35]. These networks illustrate a biologically established amplification principle: a small initiating signal can produce a much larger tissue-scale response. Suitable endpoints include ROS/redox markers, malondialdehyde, proline, antioxidant enzymes, electrophysiological measures and, in model systems, calcium reporters or targeted gene expression.

4.4 Rhizosphere and nutrient-acquisition pathway

The rhizosphere is a dynamic interface shaped by root exudates, soil chemistry and microbial communities [36,37]. Plant-microbial interactions can materially influence resource acquisition and nutrient availability [38,39]. Nutrient-acquisition strategy is also associated with microbiome structure and function [40]. QREC-Agri can therefore be tested for rhizosphere-mediated outcomes without assuming direct microbial action. Measurements may include available N, P and K, soil enzyme activities, microbial biomass, respiration, root traits, targeted functional genes and, when justified, amplicon sequencing or metagenomics.

4.5 Biological amplification and scale

A common objection to low-energy or remote interventions is the apparent mismatch between a small initiating perturbation and a large final phenotype such as increased biomass. Biology contains legitimate amplification mechanisms: ion channels, phosphorylation cascades, hormones, ROS waves, electrical signals, gene regulation and microbial interactions can transform small signals into system-wide responses. The energy for downstream change is

supplied by metabolism and the environment. This establishes the plausibility of biological amplification in general, not QREC-Agri specifically. Support for QREC-Agri would require an ordered and reproducible sequence linking intervention, an early pathway-specific marker, downstream physiology and the final agronomic outcome, ideally with mediation analysis or targeted perturbation of the candidate pathway in later studies.

Table 3 maps each candidate process to a QREC-Agri working hypothesis, measurable endpoints and the principal interpretive caution.

Table 3: Mechanism-to-measurement map for candidate QREC-Agri pathways.

Established process	QREC-Agri working hypothesis	Primary measurements	Interpretive caution
Photosynthetic excitation / electron transfer	Treatment may perturb kinetics or regulation within the light-reaction chain.	Fv/Fm, ΦPSII, NPQ, ETR, gas exchange, chlorophyll/SPAD	A fluorescence change is not evidence of quantum mediation.
PCET / enzymatic H-transfer	Treatment may alter reaction kinetics in quantum-sensitive chemistry.	Redox state, enzyme kinetics; isotope-sensitive studies in advanced work	Tunnelling is established in some enzymes, not as a QREC target.
Water / membrane transport	Treatment may alter water-ion dynamics or membrane-transport regulation.	pH, EC, ORP, DO, leaf water potential, stomatal conductance, aquaporin expression	Avoid persistent water-structure claims without direct spectroscopy.
Electrical / Ca^{2+} / ROS signalling	A small perturbation may be amplified by systemic signalling.	ROS, SOD/CAT/POD, proline, MDA, electrophysiology, expression markers	Stress, circadian state and handling can confound measurements.
Rhizosphere / microbiome	Plant or soil responses may alter nutrient cycling and microbial recruitment.	Available NPK, enzymes, microbial biomass, sequencing, root traits	Microbiome changes may be consequences rather than causes.

4.6 Prospective pathway predictions and falsifiers

A rigorous mechanistic programme should state not only what may change, but what temporal pattern would support each pathway and what observation would weaken it.

The corresponding prospective temporal predictions and pathway-specific falsifiers are set out in Table 4.

Table 4: Prospective pathway-level predictions and falsifiers.

Candidate pathway	Earliest expected signal	Downstream coherence expected	Observation that weakens the pathway
Photosynthetic	Pre-yield shift in ΦPSII, NPQ, ETR, gas exchange or chlorophyll fluorescence	Carbon assimilation and/or biomass change in a compatible direction	Repeated yield effect with no reproducible photosynthetic or gas-exchange change under adequate measurement sensitivity
Water-ion / membrane	Change in leaf or substrate water potential, stomatal conductance, transpiration, EC/ORP or aquaporin regulation	Water-use efficiency, nutrient uptake and growth shift coherently	No hydraulic, stomatal or ion-transport signal despite a replicated phenotype claimed to arise through this pathway
Electrical / Ca^{2+} / ROS	Early electrophysiological, Ca^{2+}, ROS/redox or antioxidant response	Stress physiology and later growth/quality responses follow temporally	Candidate signalling markers remain unchanged or move after,

			rather than before, the phenotype
Rhizosphere / nutrient	Early shift in available nutrients, enzyme activity, microbial biomass/function or root exudate profile	Tissue nutrient status, root traits and growth change consistently	Microbiome/nutrient changes occur only after the plant phenotype or fail independent replication

5 CAUSAL INFERENCE, FALSIFICATION AND EVIDENTIARY THRESHOLDS

The central methodological principle is to avoid mechanism-by-label. A robust treatment-control difference establishes an empirical effect only for the tested population, protocol and conditions; statistical significance alone is insufficient. Inference should be based on a pre-specified estimand, effect size, uncertainty, protocol fidelity and replication. Potential classical explanations include thermal gradients, conventional electromagnetic exposure, irrigation differences, soil heterogeneity, operator behaviour, sampling bias, weather, disease pressure, edge effects, management timing and analytical drift. These should be measured, randomised, balanced or otherwise controlled before a more unusual physical interpretation is considered.

Figure 4 summarises the staged falsification logic used to progress from an observed treatment effect towards a defensible physical-mechanism claim.

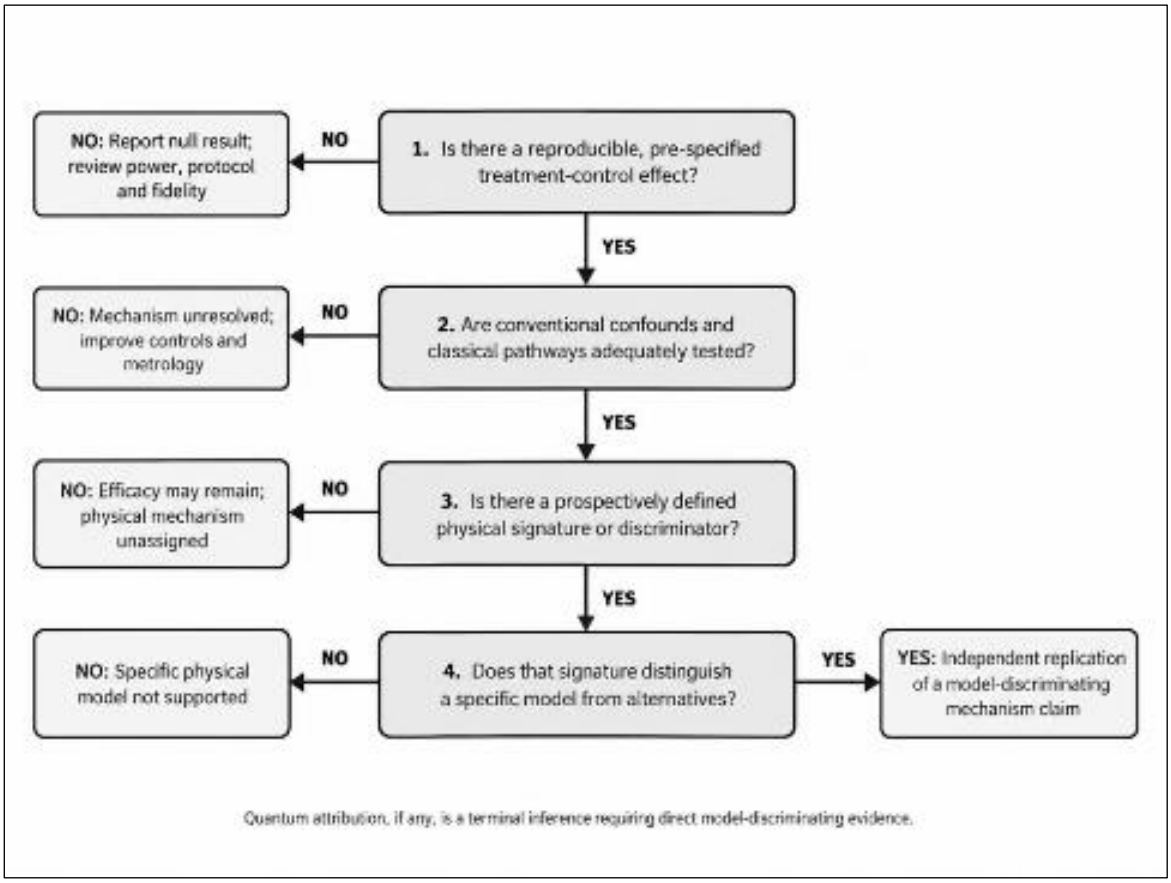


Figure 4: Falsification framework for interpreting QREC-Agri outcomes.

The principal classical confounds that could mimic or obscure a QREC-Agri treatment effect, together with the corresponding controls and measurements required to address them, are summarised in Table 5.

Table 5: Classical confounds and corresponding controls.

Potential confound	Control / measurement	Reason
Temperature / heat	Continuous or matched temperature logging in treatment, sham and control units.	Excludes thermal stimulation or microclimate bias.
Ambient EM fields	Background RF/ELF/magnetic monitoring when mechanism studies require it.	Tests whether conventional field exposure differs among groups.
Soil heterogeneity	Baseline soil chemistry, blocking/randomisation and independent plot replication.	Reduces fertility gradients being mistaken for treatment.
Water / irrigation	Metered irrigation, water chemistry and identical schedules.	Water is a dominant driver of biomass and yield.
Operator effects	Coded assignment, blinded sampling and standardised management.	Reduces expectancy and handling bias.
Weather / position	Interspersed plots, weather station and edge-effect management.	Controls spatial and temporal environmental gradients.
Multiplicity	Pre-register primary outcome and analysis hierarchy.	Reduces selective reporting and false-positive risk.
Pseudoreplication	Apply treatment independently to replicated experimental units.	Subsamples within one treated plot are not independent replicates [41,42]. Repeated measurements are not equivalent to independent replication [43].

6 PRE-SPECIFIED FALSIFIABLE PREDICTIONS

- Reproducibility: independently treated experimental units show a directionally consistent effect relative to matched controls.
- Temporal ordering: mechanistic markers expected to precede growth change before or alongside final biomass or yield.
- Specificity: the response differs from sham-treated and untreated control units and follows the pre-specified intervention rather than generic handling or site effects.
- Boundary conditions: effect magnitude varies systematically with biologically relevant state variables such as crop stage, water status or nutrient condition.
- Cross-scale coherence: mechanistic changes are directionally compatible with downstream physiology and agronomic performance.
- Independent portability: at least one external team reproduces a pre-specified endpoint using a protocol fixed before data collection.
- Exposure-response structure: if the proprietary configuration contains a prospectively controllable parameter, response should show a reproducible parameter-response relation; if no such parameter is scientifically exposed, no dose-response claim should be made.

The corresponding null hypothesis is that QREC-Agri produces no effect beyond expected biological, environmental and analytical variability. A well-powered trial that fails to reject the null should be reported as a null result for the tested configuration, not reinterpreted after the fact by searching additional endpoints.

6.1 Evidence ladder and claim discipline

Table 6 defines the evidence level required for progressively stronger claims, from hypothesis generation to a mechanism-specific quantum interpretation.

Table 6: Evidence ladder for QREC-Agri.

Level	Evidence	Claim justified
0	Anecdotal observation	Hypothesis generation only.
1	Repeatable within-site association	Association under local conditions.
2	Randomised replicated treatment-control difference	Treatment effect supported in that experiment.
3	Blinded and independently replicated effect	Robust empirical efficacy evidence.
4	Consistent temporal physiological/biochemical pathway evidence	Biological mechanism is supported.
5	Direct physical signature discriminating competing models	A specific physical mechanism becomes testable.
6	Independent reproduction of the discriminating physical mechanism	Strong basis for a mechanism claim.
7	Direct quantum observable or validated quantum witness where applicable	A quantum-mechanistic claim may be considered, limited to the measured phenomenon.

6.2 Model comparison rather than mechanism-by-exclusion

Failure to detect a known classical confound is not positive evidence for a non-classical mechanism. Competing physical models should therefore be compared using predictions specified before data inspection. Where models are sufficiently quantitative, likelihood-based or Bayesian model comparison can complement conventional estimation by asking which model best predicts the joint pattern of exposure, early mediator and outcome data. A non-classical model should gain support only by correctly predicting an observation that a well-specified classical alternative does not.

This requirement prevents a 'quantum of the gaps' inference in which unexplained residual variation is relabelled as quantum. Residual effects after classical controls justify additional mechanism research; they do not, by themselves, identify the residual mechanism.

7 INDEPENDENT VALIDATION PROTOCOL FOR AGRICULTURAL TRIALS

A scientifically useful first-stage evaluation should be simple enough to execute correctly and rigorous enough to support a decision. The recommended design follows standard agricultural experimental principles and explicitly addresses pseudoreplication [41,42]. The experimental unit is the smallest unit to which QREC-Agri is independently assigned. Multiple plants sampled within one treated plot are subsamples, not independent treatment replicates; repeated measurements must not be confused with independent replication [43].

7.1 Design, randomisation and blinding

At field scale, a randomised complete block design, incomplete-block design or spatially optimised design should be selected according to site heterogeneity and operational constraints. Treatment, sham and untreated control units may be interspersed only when cross-unit interference is plausibly negligible. Because QREC-Agri is proposed as a remote intervention, this assumption cannot simply be taken for granted. If treatment could influence neighbouring or otherwise linked control units, the stable-unit treatment-value assumption is violated and ordinary plot-level contrasts may be biased. In that case, spatially separated clusters, buffer zones, multi-site randomisation or a design that explicitly estimates direct and spillover effects should be used [44]. There is no universal minimum number of plots for inferential work: the number of independent experimental units must follow prospective power or precision planning based on the primary estimand, expected variance and the smallest agronomically meaningful effect. Very small demonstrations may be useful for logistics or reconnaissance but should not be presented as confirmatory evidence. Where remote treatment permits it, coded target allocation can support blinding of field personnel, samplers and laboratory analysts; the allocation key should remain inaccessible to analysts until the pre-specified analysis is locked. For a high-stakes confirmatory experiment, a Registered Report or equivalent protocol reviewed before outcome data are known would provide the strongest protection against publication bias and analytic flexibility [45].

7.2 Baseline and treatment fidelity

Baseline characterisation should precede activation and include crop identity, cultivar, developmental stage, density, soil texture where relevant, pH, EC, organic matter, key nutrients, irrigation-water chemistry and recent management history. Weather, irrigation, fertiliser, crop-protection inputs and protocol deviations should be recorded throughout.

Treatment fidelity should be documented through coded target identifiers, time-stamped intervention events, the intervention schedule and a locked allocation record held by an independent coordinator where feasible. Because the initiating physical exposure is not yet measurable, such process-level auditability is essential for distinguishing treatment-assignment errors from biological non-response.

7.2.1 Negative controls, sentinel units and cross-target contamination

A remote-intervention study should include controls that can reveal procedural artefacts as well as biological effects. At minimum, the design should include sham-assigned biological units that undergo the same identification, scheduling and sampling workflow as treated units. Where feasible, non-target sentinel units or geographically separated decoy targets can be included to test whether responses occur outside the pre-specified target set. Environmental sensors should be logged identically across groups.

A dedicated contamination test should be considered before large field trials. The objective is to determine whether assignment of one unit changes outcomes in another unit as a function of distance, adjacency or shared infrastructure. Evidence of such interference would not invalidate the technology hypothesis, but it would invalidate standard independent-unit analyses and require cluster-level or interference-aware causal methods.

7.3 Endpoint hierarchy

The proposed endpoint hierarchy is shown in Table 7, separating commercial outcomes from physiological, rhizosphere and physical-mechanism measurements.

Table 7: Hierarchical endpoints for QREC-Agri validation.

Tier	Domain	Examples	Purpose
1	Commercial / agronomic	Marketable yield, grade, water use, input use, harvest index	Determines practical value.
2	Whole-plant physiology	Biomass, leaf area, root mass, SPAD, stomatal conductance	Links outcome to plant performance.
3	Mechanistic physiology	Fv/Fm, ΦPSII, NPQ, gas exchange, ROS markers, antioxidant enzymes	Tests candidate biological pathways.
4	Soil / rhizosphere	pH, EC, available NPK, microbial biomass, enzymes, sequencing	Tests soil and microbiome pathways.
5	Physical / molecular	Spectroscopy, isotope effects, spin/frequency response, field measurements	Required for stronger physical-mechanism claims.

7.4 Statistical analysis and decision rules

The analysis plan should be written before treatment codes are revealed and should define the experimental unit, primary estimand, smallest effect size of practical interest, covariates, multiplicity strategy and missing-data rules. For repeated measurements, mixed-effects models are often appropriate, with treatment, time and treatment × time as fixed effects and block and experimental unit as random effects where justified. Baseline adjustment can improve precision when specified prospectively. Effect estimates and 95% confidence intervals should be reported alongside P values; interpretation should distinguish statistical compatibility from agronomic importance. Secondary endpoints should follow a pre-specified hierarchy, false-discovery procedure or explicit exploratory designation. Outlier handling and transformations should be defined before unblinding.

$$Y_{ijkt} = \beta_0 + \beta_1 T_i + \beta_2 t + \beta_3 (T_i \times t) + u_j + v_k + \varepsilon_{ijkt}$$

where Y_{ijkt} is the observed outcome for treatment group i, block j, experimental unit k, at time t; β_0 is the intercept; T_i denotes treatment assignment; β_1 represents the treatment effect; β_2 represents the effect of time; β_3 represents the treatment-by-time interaction; u_j and v_k are random effects for block and experimental unit, respectively; and ε_{ijkt} is the residual error.

The appropriate statistical model should be selected according to the experimental design, distribution of the endpoint and sampling structure. Field experiments exhibiting spatial heterogeneity may additionally require spatial covariance structures or geostatistical terms. Bayesian hierarchical models may also be considered when the inferential objective is to estimate the posterior probability that a treatment effect exceeds a pre-specified agronomically meaningful

threshold. Such analyses should complement, rather than replace, transparent reporting of group-level summaries, effect estimates, confidence or credible intervals, and associated uncertainty.

7.4.1 Interpreting null results and practical equivalence

Failure to achieve $P < 0.05$ is not evidence that an agronomically meaningful effect is absent. Before data collection, the trial should define a smallest effect size of interest (SESOI) or minimum commercially meaningful difference for the primary endpoint. If a confirmatory study is designed with adequate precision, equivalence testing or confidence-interval reasoning can then assess whether effects at least as large as that threshold are incompatible with the data [46]. This is especially important for a falsifiable technology programme because it allows a well-designed null experiment to exclude effects large enough to matter, rather than merely producing an inconclusive non-significant result.

Precision planning should also consider the risk of sign and magnitude exaggeration in small, noisy studies. Designs that are technically powered only to cross a significance threshold can still yield unstable or inflated estimates; prospective design calculations should therefore evaluate plausible effect sizes and the probability of materially overstating them [47]. Interpretation should emphasise effect estimates, uncertainty, replication and practical thresholds rather than a binary P-value decision [48].

Table 8 translates these principles into prospective go, hold, escalation and stopping decisions.

Table 8: Example pre-specified decision gates for staged evaluation

Decision gate	Suggested criterion	Interpretation
Go to confirmatory trial	Primary endpoint shows a pre-specified, practically meaningful effect with acceptable uncertainty and no major protocol imbalance.	Replicate independently with stronger blinding and mechanism measurements.
Mechanism escalation	Efficacy replicates and at least one early biological marker shows temporally coherent change.	Test the most plausible pathway with targeted instrumentation.
Hold / redesign	Effect direction is unstable, confidence interval spans trivial and meaningful effects, or important confounds are imbalanced.	Do not claim efficacy; improve design or power.
Stop tested configuration	Adequately powered, high-fidelity replication is consistently null.	Reject or materially revise the tested configuration.

The proposed workflow for independent QREC-Agri validation, integrating pre-registration, coded allocation, blinded monitoring, statistical safeguards and mechanism-specific controls, is summarised in Figure 5.

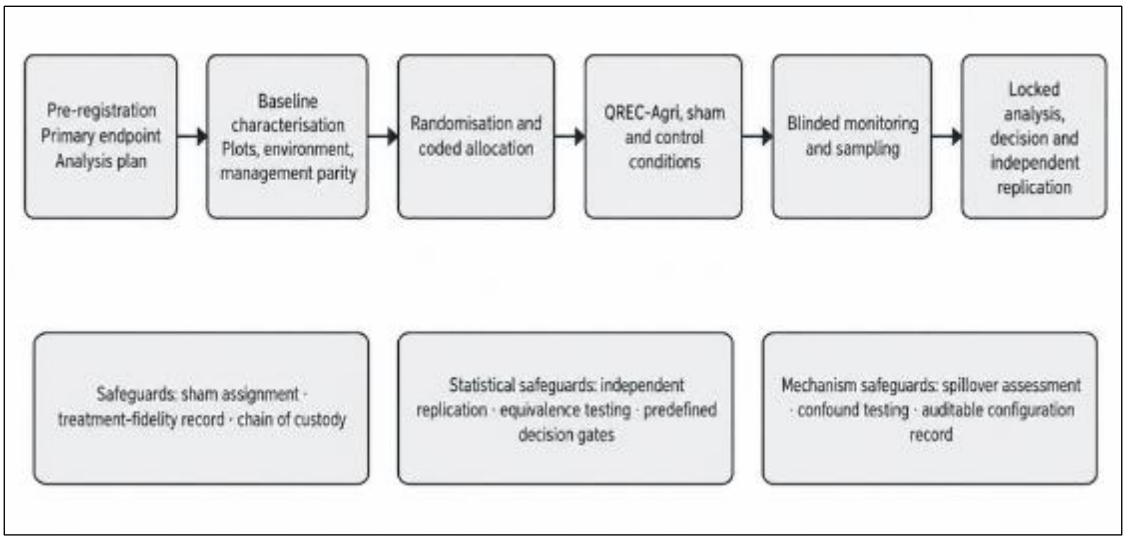


Figure 5: Independent validation architecture for QREC-Agri.

8 REPORTING, REPRODUCIBILITY AND INTELLECTUAL-PROPERTY BOUNDARIES

Proprietary implementation creates a genuine tension between intellectual-property protection and mechanistic reproducibility. It need not prevent a valid efficacy test: an independent third party can verify allocation, timing, protocol fidelity and outcomes without receiving the full proprietary configuration. However, increasingly specific physical claims require increasingly specific disclosure or controlled-access verification. A mechanism cannot be independently reproduced unless investigators can recreate, audit or otherwise verify the relevant exposure conditions and measure the predicted physical observable.

For plant phenotyping datasets, metadata should be recorded with sufficient detail to support interpretation and reuse. The MIAPPE framework provides a useful standard for describing study design, biological material, environmental conditions, treatments and observation variables [49]. For QREC-Agri trials, a MIAPPE-compatible record supplemented by treatment-allocation metadata, timestamps and chain-of-custody information would materially improve reproducibility.

8.1 Minimum disclosure threshold for a publishable efficacy claim

Commercial confidentiality can protect implementation details, but not the information required to audit the scientific claim. For a publishable efficacy study, the minimum independently auditable record should include target identity, allocation, timing, treatment state, prespecified outcome definitions, protocol deviations, laboratory chain of custody and the locked statistical plan. The exact proprietary configuration may remain sealed if an independent custodian can verify that it was fixed before unblinding and was not altered retrospectively.

Table 9 distinguishes information that may remain proprietary at the efficacy stage from information that must remain independently auditable.

Table 9: Minimum disclosure boundary between protected implementation and independently auditable science.

Information class	May remain proprietary at efficacy stage	Must be independently auditable
Algorithm / configuration internals	Yes, subject to journal/editorial requirements	Evidence that the configuration was fixed prospectively
Target identity and treatment state	No	Yes: coded target IDs, allocation key and timestamps
Treatment schedule	Only detailed internal logic may remain proprietary	Yes: start/stop times, number of interventions and deviations
Outcome definitions and analysis	No	Yes: primary estimand, endpoint, exclusions, model and multiplicity strategy
Mechanism claim exposure variables	Not if used to support a physical mechanism claim	Yes: sufficient information to reproduce or independently verify the discriminating observable

Data integrity is especially important in remote-intervention studies. Confirmatory trials should be pre-registered before treatment allocation is revealed, with the primary estimand, endpoint, exclusion rules, statistical model and multiplicity strategy time-stamped in advance [50]. A robust record should include a locked plot map, allocation key held independently until analysis, timestamped treatment events, weather and irrigation logs, analytical chain of custody, laboratory certificates, predefined exclusions and a version-controlled statistical analysis plan. For proprietary configurations, a trusted third party may retain a time-stamped or cryptographically hashed configuration record so that the exact configuration used in a trial can later be verified without public disclosure. These practices protect both sceptical evaluators and the technology developer from ambiguous post hoc interpretation. These practices align with broader reproducibility and transparency principles that prioritise auditable methods, prospective specification and independent verification over trust in the originator [51,52].

The minimum reproducibility record recommended for each evaluation is summarised in Table 10.

Table 10: Minimum data package for reproducible QREC-Agri evaluation.

Category	Minimum recommended record
Site and crop	Site identifier retained by evaluator; crop, cultivar, sowing/transplant date, density and developmental stage.
Allocation	Coded treatment/sham/control assignment, plot map, randomisation method and activation timestamps.
Environment	Daily weather, irrigation quantity, major soil/water variables and unusual events.
Inputs	Fertiliser, pesticide, biostimulant and other inputs with dates and rates.
Measurements	Primary endpoint plus pre-specified physiology/soil endpoints and measurement schedule.
Sampling	Sample IDs, dates, chain of custody, laboratory methods and analytical uncertainty.
Statistics	Experimental unit, n per arm, model, effect size, confidence interval, multiplicity and missing-data handling.
Treatment fidelity	Target identifier, treatment schedule, deviations and independent audit trail.

9 DISCUSSION

The value of the proposed framework is that it makes a mechanistically unresolved technology testable without requiring prior agreement about its mechanism. Efficacy and mechanism frequently mature at different rates in emerging interventions. A reproducible agronomic effect can justify further study even when the initiating physical mechanism remains unresolved; conversely, mechanistic speculation cannot substitute for a reproducible phenotype. This asymmetry is especially important for QREC-Agri because the intervention is remote and its exposure variable is not yet publicly metrologised.

The strongest near-term evidence for QREC-Agri would therefore not be a broad catalogue of positive crop observations. It would be a small number of independently replicated studies with pre-registered endpoints, credible randomisation, coded allocation, treatment fidelity, blinded sampling, complete environmental records and effect sizes large enough to matter agronomically. Mechanistic measurements should be selected because they discriminate plausible pathways, not because they create a large search space in which some variable is likely to reach statistical significance.

The quantum-science component should be treated with equal discipline. The relevant physical building blocks are not new: quantised molecular states, resonance, electron/proton transfer, tunnelling and spin chemistry are established domains of physics and physical chemistry. Photosynthetic energy transfer and coherence provide one established biological context [6,12]. Proton-coupled electron transfer and enzymatic tunnelling provide another [8,10]. Radical-pair chemistry provides a further quantum-sensitive example [13,14]. What is new and therefore evidentially demanding is the claim that a proprietary remote intervention can engage such processes in a target-specific and reproducible manner. These established phenomena do not imply that an arbitrary remote intervention can control them. For QREC-Agri, quantum attribution would require a prospectively specified observable derived from a physical model and capable of distinguishing that model from classical alternatives. Depending on the model, such evidence might involve isotope dependence, a spin-selective response, a reproducible resonance curve, phase dependence, spectroscopy or another accepted quantum-sensitive observable. The appropriate test must be chosen before, not after, observing a crop response.

A further requirement is quantitative closure. If a future model invokes an electromagnetic, acoustic, thermal or other classical carrier, field strength, spectral content, attenuation, energy deposition and expected biological sensitivity should be estimated against measured backgrounds. If it invokes a genuinely non-classical process, the model must specify an observable that cannot be reproduced by an adequate classical model. Without this step, the word 'quantum' remains contextual rather than explanatory.

The proposed framework also has translational value for independent pre-commercial evaluations. An external partner does not need to endorse the underlying quantum hypothesis to participate in a valid trial; it needs only to agree prospectively on experimental units, management parity, primary endpoints, sampling, treatment-fidelity records, analysis and decision thresholds. This separation between operational testing and mechanistic belief allows commercial evidence generation to remain scientifically interpretable.

Beyond QREC-Agri, the framework contributes a general demarcation strategy for emerging technologies in which the phenotype may be easier to measure than the initiating exposure. Its central principle is that uncertainty about mechanism should increase experimental discipline, not lower the evidentiary threshold. A credible programme must make success and failure equally interpretable.

The proprietary intervention is not fully characterised by a public exposure model, no new efficacy dataset is reported here, and the candidate pathways are deliberately broad. The most important unresolved issues are therefore identifiability of the initiating exposure, the possibility of interference between experimental units, and the risk that a flexible proprietary configuration could be altered retrospectively after an unfavourable trial. The framework addresses these risks through locked assignments, pre-specified configuration records, sham targets, independent replication, prospective stopping rules and explicit separation of exploratory from confirmatory analysis. These safeguards do not establish efficacy; they make an efficacy claim capable of being credibly tested.

10 RESEARCH PROGRAMME AND PRIORITY EXPERIMENTS

Table 11 organises the proposed research programme into five stages, from efficacy screening to independent replication of a discriminating physical mechanism**.**

Table 11: Staged QREC-Agri research programme.

Stage	Primary question	Preferred design	Key output
I. Efficacy screen	Does a reproducible agronomic or physiological effect exist?	Randomised replicated treatment/sham/control study with blinded measurement; prior or embedded spillover/contamination check.	Effect size, CI, protocol fidelity and replication status.
II. Pathway localisation	Which biological pathway changes first?	Dense temporal sampling of one or two candidate pathways.	Temporal ordering and mediation-compatible evidence.
III. Classical exclusion	Can thermal, EM, environmental or handling pathways explain the effect?	Instrumented exposure/control study with metrology.	Residual effect after measured classical pathways are modelled.
IV. Physical mechanism	Does a specific physical model predict a discriminating signature?	Purpose-built laboratory study with model-specific observable.	Resonance curve, isotope/spin/phase/spectroscopic or other discriminating signature.
V. External replication	Can another team reproduce the efficacy and mechanism?	Independent site/laboratory using locked protocol.	Generalisation and mechanism reproducibility.

11 CONCLUSIONS

QREC-Agri is best treated at present as a scientifically testable intervention rather than as an established quantum technology. The scientifically distinctive claim of this article is therefore not that a remote quantum mechanism has been demonstrated, but that the proposition can be decomposed into separable causal and physical questions with explicit evidentiary thresholds. The working hypothesis is that a targeted non-contact intervention may alter molecular, supramolecular or regulatory processes, after which endogenous biological networks may amplify the initiating perturbation into measurable plant-soil-water responses. Established science identifies tractable domains in which such responses can be sought, including photosynthetic energy transfer, proton/electron chemistry, water and membrane transport, electrical/Ca^{2+} /ROS signalling and rhizosphere-mediated nutrient acquisition. The framework therefore places QREC-Agri within an established physical lineage of resonance, quantised molecular dynamics and biological signal amplification while treating the claimed remote, target-specific coupling as the genuinely novel and testable element.

The decisive questions are sequential. First, does a reproducible, pre-specified effect exist with adequate protocol fidelity and independent replication? Second, what biological pathway mediates it? Third, can measured classical physical mechanisms account for the observation? Fourth, if an unexplained residual remains, does a pre-specified physical model predict a discriminating signature? Only after those steps should a non-classical or quantum-mechanistic interpretation be considered. This ordering converts QREC-Agri from a broad technology proposition into a programme of falsifiable hypotheses, measurable transitions and explicit stopping rules.

For agricultural companies and research institutions, this architecture permits immediate empirical evaluation without prior commitment to the proposed mechanism. For the scientific programme, it provides a route from agronomic observation to physiology, molecular mechanism and, only if supported by discriminating evidence, a deeper test of quantum-sensitive coupling.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The author is involved in the development and evaluation of QREC-MRT™/QREC-Agri and has a professional and/or proprietary interest in the technology. This relationship is disclosed for transparency.

Data availability

This article does not report a new primary dataset. Data generated in subsequent validation studies should be archived with sufficient metadata to permit independent assessment and reuse, subject to legitimate commercial and privacy constraints.

Intellectual property

Detailed proprietary implementation parameters are outside the scope of this manuscript. Their non-disclosure does not preclude blinded efficacy testing but may limit mechanistic reproducibility until controlled-access or independent audit arrangements are established.

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