Quantum-Resonant Energy Coupling–Molecular Resonance Technology: A Quantitative and Falsifiable Multidomain Validation Framework with an Exploratory Coal Case Study

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Abstract

Aims: Quantum-Resonant Energy Coupling–Molecular Resonance Technology (QREC-MRT) is a remotely implemented, non-contact technology platform intended for application across selected material, energy and biological systems. This study develops a quantitative, physics-informed and falsifiable framework for evaluating QREC-MRT and uses coal as a worked empirical case study. The physical coupling pathway is treated separately from target identification and remains under investigation.

Methodology: Two coal specimens identified as before and after QREC-MRT intervention were independently analysed by SGS India Private Limited. Gross calorific value (GCV) was measured using ASTM D5865/D5865M-19 and analysis-sample moisture using ASTM D3173/D3173M-17a. Absolute and relative between-specimen differences were calculated. A broader validation model was formulated using prespecified endpoints, normalised responses, active-control and active-sham contrasts, replication requirements and progressively stronger evidentiary levels.

Results: Air-dry GCV increased from 4,057 to 5,160 kcal/kg, corresponding to +27.20%, while dry-basis GCV increased from 4,122 to 5,206 kcal/kg, corresponding to +26.30%. Analysis-sample moisture decreased from 1.57% to 0.88% w/w, corresponding to −43.95%. Moisture normalisation reduced the relative GCV difference by only 0.90 percentage points, indicating that the measured moisture difference alone cannot mathematically account for the observed calorific-value difference.

Conclusion: The coal measurements provide quantitative observational endpoints consistent in direction with the QREC-MRT coal hypothesis, but the available single paired dataset does not establish treatment-specific causation because untreated and sham controls, randomisation, blinding, independent replicates, paired compositional analyses and complete pre-laboratory chain-of-custody documentation were unavailable. The proposed framework therefore separates analytical observation, reproducibility, controlled treatment association and physical mechanism. Coal serves as the present empirical case study, while the same validation architecture can be adapted to other QREC-MRT domains using appropriate endpoints, controls and independent measurements.

Keywords: QREC-MRT; quantitative validation; molecular resonance; falsifiability; coal; gross calorific value; experimental design.

1. Introduction

Quantum-Resonant Energy Coupling–Molecular Resonance Technology (QREC-MRT) is proposed as a remote, non-contact technology platform intended to produce measurable changes in selected material, energy and biological systems without direct chemical addition, physical mixing or permanent modification of target infrastructure. Proposed application areas include solid, liquid and gaseous fuels, photovoltaic systems, agriculture and biological-response systems. The present manuscript does not attempt to establish equivalent evidentiary maturity across all of these domains; instead, it develops a common quantitative validation framework and uses coal as the worked empirical case study.

Operationally, the intended target may be identified remotely using photographs, latitude-longitude coordinates and associated target metadata, allowing the intervention to be implemented without QREC-MRT equipment or personnel being physically present at the target location. These identifiers specify the intended target within the operational protocol and are not presented as the physical coupling or energy-transmission mechanism.

QREC-MRT is treated in this paper as an experimentally testable intervention rather than solely as a theoretical construct. The purpose of the present study is to place its reported operational characteristics within a quantitative and falsifiable scientific framework in which measurable outcomes can be independently tested, reproduced and, where reproducibility is established, progressively related to an underlying physical mechanism.

Resonance-energy transfer depends on spectral compatibility, molecular separation, orientation and coupling strength [1,2]. Short-range exchange transfer imposes additional spatial and orbital-overlap constraints [3]. Open-system studies demonstrate that environmental interactions can influence transport efficiency in complex molecular systems [4,5]. Related theoretical work has examined these effects under physiologically relevant conditions [6].

Quantum effects have also been investigated in biological energy-transfer systems. Coherent behaviour has been reported in photosynthetic complexes [7,8], while broader work in quantum biology has examined coherence, tunnelling, spin dynamics and related phenomena [9,10]. Subsequent work has questioned whether long-lived electronic coherence is required for efficient photosynthetic energy transfer [11,12]. Broader analyses have emphasised the importance of distinguishing electronic coherence from vibrational, vibronic and illumination-dependent effects [13,14]. Engineered photosynthetic systems nevertheless demonstrate that energy and electron-transfer pathways can be modified under appropriately controlled physical conditions [15,16]. Advances in quantum metrology and sensing similarly

illustrate the experimental precision required when a specifically quantum mechanism is proposed [17,18].

These established phenomena provide scientific context for QREC-MRT but do not themselves establish its proposed remote macroscopic coupling pathway. Any such physical interaction must ultimately be characterised through measurable source, exposure, target-response and uncertainty variables. Electromagnetic-exposure science demonstrates the importance of field characterisation, dosimetry and environmental control [19,20]. Systematic reviews of radiofrequency exposure demonstrate substantial variation in experimental systems and exposure conditions [21,22]. Dosimetry and physical exposure configuration can materially affect interpretation [23,24]. Human experimental and reproductive studies further illustrate the importance of endpoint-specific study design [25,26]. Epidemiological and symptom-based assessments similarly require careful separation of exposure, outcome and confounding variables [27,28]. More recent evaluations reinforce the importance of reproducibility and clearly defined outcome measures [29,30].

The present study therefore separates four progressively stronger levels of evidence: analytical observation, reproducibility, controlled treatment association and physical mechanism. A measurable difference between defined observations can be evaluated directly. Reproducibility requires the same directional response across independently prepared experimental units. Controlled treatment association requires active intervention to remain distinguishable from appropriate sham and untreated comparison conditions. Mechanistic attribution requires additional measurements capable of distinguishing among competing physical explanations.

The principal empirical case study examined here consists of independent analysis of coal specimens identified as before and after QREC-MRT intervention. Gross calorific value increased from 4,057 to 5,160 kcal/kg on an air-dry basis, corresponding to +27.20%. On a dry basis, GCV increased from 4,122 to 5,206 kcal/kg, corresponding to +26.30%. Moisture in the analysis sample decreased from 1.57% to 0.88% w/w, corresponding to a relative reduction of 43.95%. The persistence of almost the entire GCV difference after conversion to a dry basis indicates that the measured difference in analysis-sample moisture alone cannot mathematically account for the magnitude of the observed calorific-value difference between the two specimens.

The available coal dataset does not, however, contain the experimental controls required to assign these differences causally to QREC-MRT. It therefore serves in this paper as a quantitative observational case study and as a source of numerical endpoints for prospective controlled validation.

This paper has four objectives: to define QREC-MRT as a quantitatively testable and falsifiable intervention; to develop a structured framework for evaluating analytical response, reproducibility and treatment association; to examine the available coal measurements within their evidentiary limits; and to provide a validation architecture

that can be adapted to other QREC-MRT application domains when appropriately controlled and independently documented datasets become available.

2. Scientific Basis and Operational Framework

2.1 Scientific Basis

A scientifically testable remote intervention requires a reproducible relationship between a defined intervention and a defined target. Established non-contact interactions include electromagnetic, acoustic, optical and thermal processes, which can be characterised through measurable quantities such as frequency, amplitude, power, exposure duration and attenuation with distance. International electromagnetic-exposure frameworks illustrate the importance of defining source characteristics and target exposure quantitatively [19].

Actual exposure can differ substantially from nominal source conditions because distance, orientation, reflections, shielding and surrounding structures may influence the interaction reaching a target [20]. Experimental evaluation of QREC-MRT should therefore document target identity, intervention timing, treatment duration, relevant environmental conditions and the analytical method used to determine the prespecified outcome.

Research on physical-exposure effects has shown that variation in dosimetry, experimental design and endpoint selection can materially influence interpretation [21,22]. Reviews of biological exposure studies similarly emphasise methodological quality, reproducibility and appropriate controls [23,24].

Target specificity is particularly relevant to QREC-MRT because the intervention is assigned to a selected sample, asset or location. Correctly targeted experimental units should therefore be distinguishable from appropriate comparison units under controlled and, where feasible, blinded analytical assessment. Sham and untreated controls can help distinguish a treatment-associated response from procedural, handling or other non-specific differences [25,26].

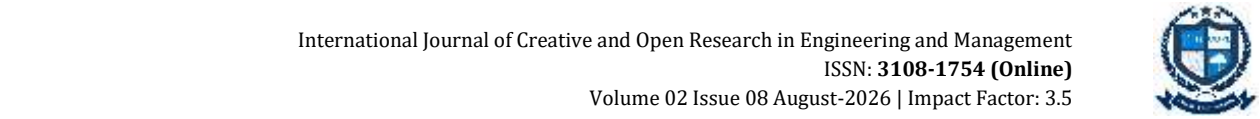
Within the quantitative framework adopted in this paper, observation of a measurable difference constitutes the first evidentiary level. Progression to a treatment-associated interpretation requires reproducibility across independent experimental units and comparison with appropriate control conditions. Identification of a physical mechanism requires an additional level of mechanism-specific evidence.

2.2 Operational Definition

QREC-MRT is operationally defined as a remote, non-contact intervention intended to produce measurable changes in a selected target without direct chemical addition, physical mixing or permanent installation of QREC-MRT hardware at the target.

For experimental purposes, the intervention comprises five principal steps:

1. target identification and characterisation;



2. selection of a target-specific treatment programme;
3. activation for a defined duration;
4. remote association of the programme with the intended target; and
5. measurement of prespecified target properties before and after intervention.

The target may comprise a material sample, fuel stock, operating asset, photovoltaic system, agricultural plot or biological system. Inclusion of these target classes defines the intended multidomain scope of the QREC-MRT platform; it does not imply that equivalent experimental evidence is available for every domain in the present paper.

Photographs, geographic coordinates, sample identifiers and associated metadata may be used to identify and distinguish the intended target. These inputs constitute an operational addressing layer. They specify which target is assigned to a particular QREC-MRT programme and are not presented as the physical energy-transfer or coupling mechanism.

The physical coupling question is separate: it concerns how the remotely initiated QREC-MRT programme may interact with the identified target. The present study does not claim that a photograph, geographic coordinate or digital record itself transfers energy to the target. The coupling pathway remains under experimental investigation and requires mechanism-specific physical evidence.

The operational sequence is therefore:

Target identification → Treatment-programme selection → Remote intervention → Hypothesised coupling → Target response → Independent measurement → Quantitative comparison

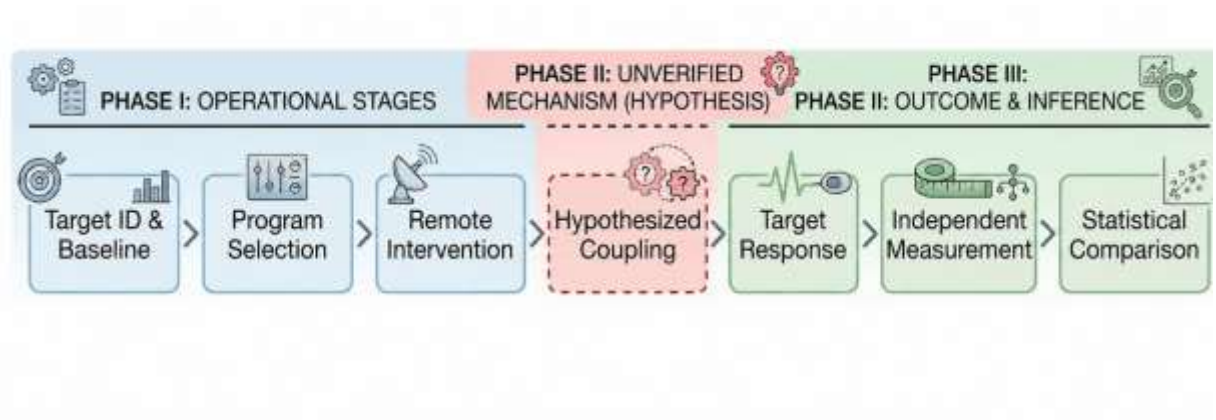


Figure 1. Operational and hypothesised components of QREC-MRT. The framework separates directly documentable operational stages from the hypothesised coupling stage.

Target identity may be established through sample codes, photographs, geographic coordinates, equipment identity or other traceable records. Treatment programmes

should likewise be assigned fixed identifiers, versions and treatment durations so that repeated applications can be compared consistently.

For experimental reproducibility, each programme should therefore be represented by a unique version-controlled identifier linked to its intended target class, activation time and treatment duration. Proprietary programme-generation details may remain confidential provided that an independent experiment can verify that the same defined programme version was applied consistently across replicated trials.

2.3 Candidate Physical Mechanisms

QREC-MRT is hypothesised to involve a target-specific physical interaction in which the response depends on characteristics of the intended target and the programme assigned to it. The working model draws on established concepts including molecular resonance, spectral compatibility, vibrational excitation, open-system energy transfer and energy-landscape dynamics. These concepts provide physically testable analogues for investigating QREC-MRT; they are not presented as proof that the remote coupling pathway has already been established.

In the operational description of QREC-MRT, the term **"**information coupling**"** refers to the defined association between a treatment programme and an identified target. It does not imply that information itself constitutes an independently established physical field or energy-transfer mechanism.

Three broad mechanistic possibilities may presently be considered:

1. **Conventional physical-field mediation:** the intervention is associated with a measurable electromagnetic, acoustic, optical, thermal or related physical interaction.
2. **Indirect technological mediation:** an observed response arises through a sensing, communication or control pathway rather than through direct interaction with the target material.
3. **Alternative physical coupling:** a reproducible target-associated response remains after experimentally testable conventional pathways have been examined and requires a different physical description.

These alternatives lead to distinguishable experimental predictions involving distance, shielding, target specificity, environmental conditions and measurable source characteristics.

If resonance contributes to a QREC-MRT response, one or more definable target or programme variables should influence that response. Established resonance-transfer systems depend on energetic compatibility, coupling strength and geometry [1,2]. Short-range exchange processes impose additional spatial constraints [3], while interaction with the surrounding environment can modify energy-transfer dynamics in complex molecular systems [4,5].

A specifically quantum interpretation represents a higher-order mechanistic hypothesis. Quantum-biological studies demonstrate that coherent and other non-classical processes can occur in defined microscopic systems [7,8], while subsequent work emphasises the need to distinguish electronic coherence from vibrational and alternative explanations [11,12]. A macroscopic QREC-MRT response should therefore not be assigned to a specifically quantum mechanism without direct mechanism-specific evidence.

Figure 2 summarises the physics-informed QREC-MRT framework. It separates operational stages that can be documented directly from the coupling stage that remains under investigation. Target identification and treatment-programme selection precede the remote, non-contact intervention. Any resulting response is subsequently assessed through independent measurement and quantitative comparison. The same framework allows an observed response to progress through replication, controlled testing and, where justified, mechanistic characterisation.

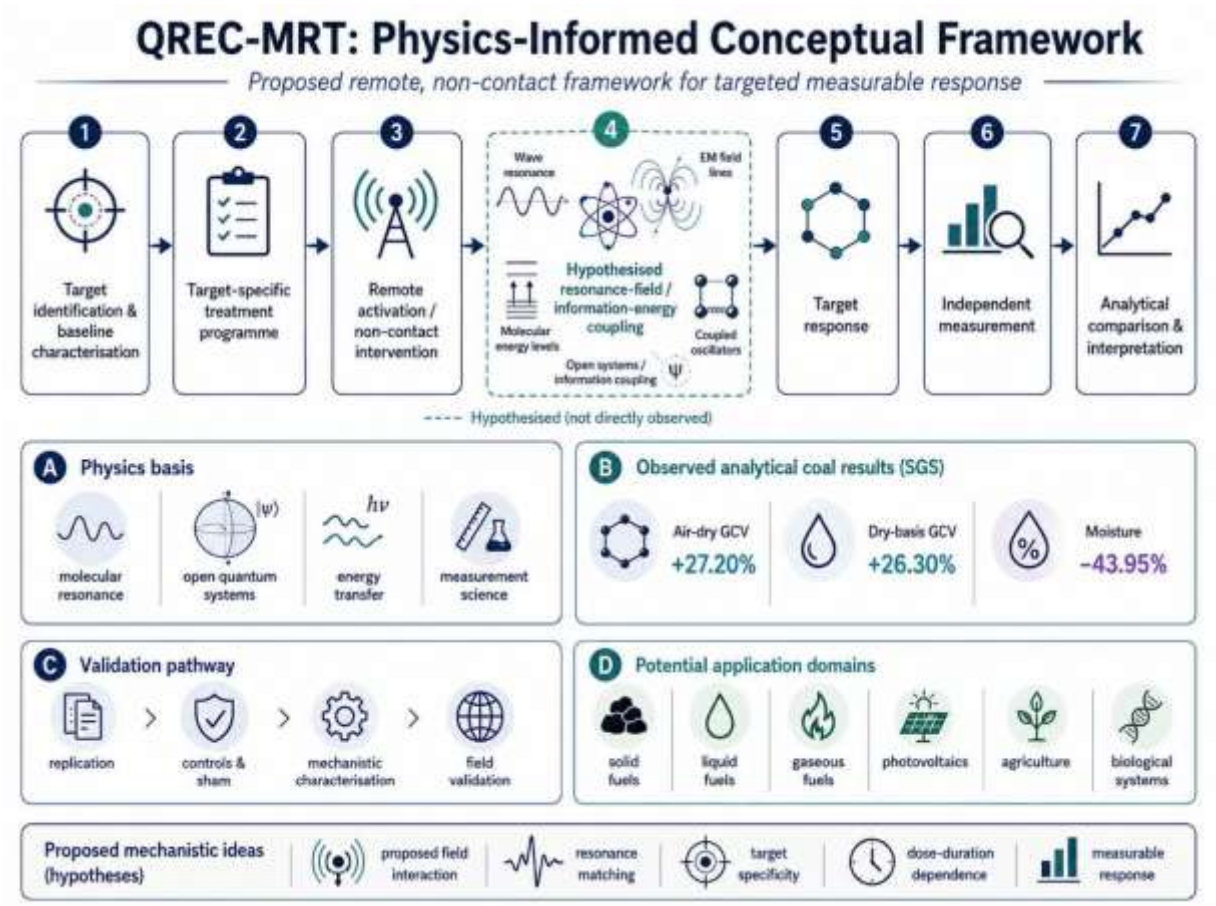


Figure 2. Physics-informed conceptual framework of QREC-MRT. The sequence extends from target identification and programme selection through remote non-contact intervention, hypothesised coupling, target response, independent measurement and quantitative interpretation. The mechanistic layer represents candidate processes that require direct experimental characterisation.

Within this framework, resonance refers to preferential coupling between an excitation and compatible molecular or collective energy modes. Molecular reconfiguration refers to a persistent alteration in material organisation that would need to be demonstrated independently through spectroscopic, structural, thermal or compositional measurements.

2.3.1 Physics-Informed Working Hypothesis for QREC-MRT

A working physical hypothesis for QREC-MRT is that a target-specific programme may interact preferentially with molecular or material degrees of freedom whose characteristic energy scales are compatible with the effective coupling conditions. In conventional resonance physics, selective energy transfer occurs when the spectral characteristics of an excitation overlap with permitted molecular, vibrational or electronic transitions. The corresponding energy scale may be expressed in its simplest quantum form as:

$$\mathbf{E = h\nu}$$

where E is transition energy, h is Planck's constant and ν is frequency. Resonance efficiency would be expected to depend not only on nominal frequency but also on spectral bandwidth, coupling strength, molecular environment, orientation and energy-dissipation pathways [1,2].

For heterogeneous materials such as coal, the target cannot be represented as a single molecular species. Coal contains an irregular carbonaceous network comprising aromatic and aliphatic structures, heteroatom-containing functional groups, mineral matter and physically or chemically associated water. A QREC-MRT programme may therefore be considered, as a working hypothesis, in relation to a distributed spectral fingerprint rather than a single discrete resonance frequency.

In such a model, O–H, C–H, C–O and other vibrational modes, together with collective structural modes of the carbon matrix, constitute candidate response channels. Environmental coupling, dephasing and redistribution of excitation energy could influence whether an initially excited state dissipates or is associated with a persistent material response [4,5].

A complementary description can be formulated using an energy-landscape model. Molecular and structural configurations occupy local energetic minima separated by activation barriers. Resonant excitation could, in principle, modify the probability with which selected molecular degrees of freedom access alternative configurations.
Under conventional molecular-kinetic descriptions, transitions depend on the relevant activation barrier and the available thermal or other excitation energy.

At microscopic scales, barrier crossing may also include quantum-mechanical contributions such as tunnelling when particle mass, barrier height and barrier width permit a non-negligible transmission probability. Such processes are established in molecular physics but are included here only as candidate explanatory mechanisms.

Their existence in other systems does not establish that tunnelling occurs during QREC-MRT intervention.

For coal, one hypothesis suitable for direct testing is that an energetic response may be accompanied by changes in molecular organisation, water binding, volatile-associated functional groups or carbon ordering. A QREC-MRT working model includes the possibility of vibrationally mediated desorption of associated water and changes in the organisation of carbonaceous structures. If such changes occur, they should generate independent experimental signatures rather than being inferred solely from calorific-value measurements.

FTIR spectroscopy could examine changes in functional-group vibrations. Raman spectroscopy could assess carbon ordering and characteristics of disordered and graphitic domains. X-ray diffraction could examine structural organisation, while thermogravimetric analysis could identify changes in thermal-decomposition behaviour.

Any field-mediated interpretation must also satisfy electromagnetic boundary conditions and energy conservation. Maxwell's equations provide the classical framework relating electric and magnetic fields to charge, current and time-varying field behaviour. A field-mediated QREC-MRT model would therefore require measurable quantities associated with source characteristics, propagation, coupling strength and absorbed energy.

If no conventional field of sufficient magnitude can be detected at the target, an observed reproducible response could not simply be attributed to conventional electromagnetic propagation. Alternative physical explanations would then require their own measurable variables and experimentally distinguishable predictions.

If resonance contributes to the QREC-MRT response, the effect should be testable against variables such as target identity, programme identity, treatment duration, distance, shielding and other coupling conditions. Where a material transformation is proposed, corresponding spectroscopic or structural changes should also be measurable.

Failure to reproduce these relationships would weigh against a resonance-based interpretation. Conversely, reproducible agreement among calorimetry, moisture analysis and independent material-characterisation methods would provide stronger evidence for a physical pathway associated with the measured macroscopic response.

2.4 Testable Predictions and Falsifiability

If a reproducible QREC-MRT response exists, it should generate experimentally testable characteristics. Depending on the application and endpoint, these may include:

- target specificity;
- programme specificity;
- treatment-duration dependence;
- latency;
- persistence;
- reversibility;
- source-to-target distance dependence; and
- sensitivity to environmental or shielding conditions.

Target specificity can be tested by comparing correctly identified targets with otherwise comparable untargeted or deliberately mismatched targets. A target-associated response would be supported if the prespecified outcome is reproduced preferentially in correctly targeted experimental units while appropriate comparison units do not show the same pattern.

Programme specificity can be examined by assigning defined, version-controlled QREC-MRT programmes to experimentally comparable targets. If the proposed interaction depends on programme-target compatibility, programme identity should contribute predictively to the measured response rather than functioning merely as an administrative label.

Treatment-duration experiments can determine whether the response exhibits threshold, progressive, saturation or delayed behaviour. Likewise, distance and shielding experiments can help distinguish among conventional field-mediated, environmentally dependent and alternative coupling models.

The QREC-MRT framework must remain falsifiable. Confidence in a treatment-associated response would decrease if active and comparison samples repeatedly behave similarly, if target or programme identity does not predict the prespecified response, or if an initially observed difference cannot be reproduced independently.

Experimental hypotheses, primary endpoints and analysis procedures should therefore be specified before examination of the final results so that interpretation is not determined retrospectively by the observed data [27]. Appropriate control conditions and transparent reporting are also required to reduce bias and post hoc reinterpretation [28,29].

The present paper distinguishes three principal inferential questions. First, was a measurable analytical difference observed? Second, is that response reproducibly associated with active QREC-MRT when compared with appropriate sham and untreated conditions? Third, what physical mechanism accounts for any reproduced treatment-associated response? Mechanistic attribution requires measurements

capable of distinguishing among competing physical explanations rather than inference from the macroscopic endpoint alone [30].

This distinction is particularly important for a multidomain platform. Different applications may employ different physical, chemical, energetic or biological endpoints, but the underlying validation logic remains the same: observation should precede replication, replication should precede treatment-specific inference, and treatment-specific inference should precede mechanism-specific conclusions.

3. Quantitative Model, Research Hypotheses and Validation Criteria

3.1 Primary Research Hypothesis

The primary quantitative question is whether QREC-MRT produces a measurable and reproducible change in a prespecified target property beyond the variation expected from sampling, measurement, and appropriate comparison conditions.

The general hypotheses are:

- **Null hypothesis (H_0):** QREC-MRT produces no treatment-associated change beyond expected experimental, sampling, and analytical variation.
- **Alternative hypothesis (H_1):** QREC-MRT produces a prespecified treatment-associated change that exceeds expected experimental, sampling, and analytical variation.

For experimental unit i, the absolute within-unit response is defined as:

$$\Delta Y_i = Y_{i,\text{post}} - Y_{i,\text{pre}}$$

where:

- $Y_{i,\text{pre}}$ = prespecified endpoint before intervention;
- $Y_{i,\text{post}}$ = corresponding endpoint after intervention.

A normalised percentage response may additionally be calculated as:

$$R_i = \left(\frac{Y_{i,\text{post}} - Y_{i,\text{pre}}}{Y_{i,\text{pre}}} \right) \times 100 \qquad \text{——————}$$

where R_i expresses the observed response relative to the baseline value.

Where treated and comparison groups are available, the treatment-associated effect may be expressed as:

$$\tau = \Delta Y_T - \Delta Y_C$$

where:

- ΔY_T = mean change in the active-treatment condition;

- ΔY_C = mean change in the comparison condition. For

paired baseline and post-intervention measurements:

$$\tau = (Y_{T,\text{post}} - Y_{T,\text{pre}}) - (Y_{C,\text{post}} - Y_{C,\text{pre}})$$

For n_T treated units and n_C comparison units, the estimated mean treatment contrast can be written as:

$$\hat{\tau} = \Delta\bar{Y}_T - \Delta\bar{Y}_C$$

Where a three-arm design includes active treatment T, sham condition S, and untreated control C, two contrasts are particularly important:

$$\tau_{TS} = \Delta\bar{Y}_T - \Delta\bar{Y}_S$$

and

$$\tau_{TC} = \Delta\bar{Y}_T - \Delta\bar{Y}_C$$

A treatment-specific interpretation requires the active condition to remain distinguishable from both comparison conditions within a prespecified uncertainty framework. A difference between active treatment and untreated control alone would not exclude procedural, handling, or expectancy-related influences if the sham condition produced a similar response.

A dimensionless treatment contrast may also be represented using normalised responses:

$$R_{\tau,C} = \bar{R}_T - \bar{R}_C$$

and, where a sham group is included:

$$R_{\tau,S} = \bar{R}_T - \bar{R}_S$$

These normalised quantities allow responses to be expressed relative to their own baselines. They should not, however, be used to combine physically different variables into a single effect measure unless an explicitly justified multivariate model has been prespecified.

The direction of the favourable response depends on the endpoint. A reduction is favourable for variables such as moisture or certain damage-related measures, whereas an increase may be favourable for endpoints such as calorific value, photovoltaic output, or agricultural yield.

Primary hypotheses and endpoints should be specified prospectively to reduce selective interpretation after results become available [31]. Where a sham condition is employed, it should reproduce the non-specific procedural elements of the intervention while excluding the proposed active component [32].

3.2 Evidentiary Decision Framework

The quantitative interpretation of QREC-MRT can be represented as a sequence of progressively stronger evidentiary states rather than as a single binary conclusion.

Let:

- E_1 = evidence of an analytical response;
- E_2 = evidence of reproducibility;
- E_3 = evidence of a controlled treatment association;
- E_4 = evidence supporting a physical mechanism. The

progression may be represented as:

$$E_4 \Longrightarrow E_3 \Longrightarrow E_2 \Longrightarrow E_1$$

The reverse implications do not necessarily follow:

$$E_1 \nRightarrow E_2$$

$$E_2 \nRightarrow E_3$$

$$E_3 \nRightarrow E_4$$

An analytical difference can therefore exist without establishing reproducibility. Reproducibility can exist without establishing that the active intervention differs from sham or untreated comparison conditions. Likewise, a controlled treatment association does not by itself identify the underlying physical mechanism.

For the present coal case study, the available evidence lies primarily at the E_1 level because a measurable before-and-after analytical difference is available, whereas the experimental controls required to evaluate E_2 and E_3 prospectively are absent.

This hierarchy provides a common quantitative structure for evaluating QREC-MRT across different application domains. The physical endpoint may change from one domain to another, but the evidentiary progression remains applicable.

3.3 Experimental Quality and Statistical Interpretation

Confirmatory experiments should use prespecified outcomes, documented allocation procedures and transparent reporting of protocol deviations. Established reporting frameworks provide guidance for reducing bias and improving reproducibility in controlled studies [33,34].

Interpretation should not depend solely on whether a conventional statistical-significance threshold is crossed. Effect magnitude, uncertainty and scientific relevance should be considered together [35]. Statistical evidence should therefore be reported without treating an arbitrary probability threshold as the sole criterion for scientific validity [36].

Where the objective is to determine whether a difference is smaller than a predefined practically meaningful threshold, equivalence testing may be appropriate [37].
Sample size should likewise be determined prospectively from expected variability, required precision and the minimum effect considered scientifically or operationally relevant [38].

Measurement interpretation should distinguish accuracy, trueness, precision, repeatability and reproducibility according to recognised measurement-science terminology [39]. Laboratory competence and analytical traceability should, where applicable, be supported through ISO/IEC 17025 accreditation or an equivalent quality framework [40].

3.4 Solid-Fuel Validation

Coal is a heterogeneous material, and representative sampling is therefore essential when comparing analytical properties among experimental portions. Bulk sampling procedures should minimise systematic differences among portions submitted for analysis [41]. Preparation of laboratory samples should likewise preserve representativeness during crushing, division and reduction [42].

Mechanical sampling provides one approach to obtaining representative increments from moving coal streams [43]. Where stationary coal must be sampled directly, appropriate manual sampling procedures should be used [44].

For QREC-MRT coal studies, the principal analytical endpoints should include gross calorific value and analysis-sample moisture. Moisture should be measured using the method identified on the laboratory certificate, including ASTM D3173/D3173M where applicable [45].

Ash should be measured concurrently because mineral matter can materially influence calorific-value interpretation [46]. A complete proximate analysis can additionally provide moisture, ash and volatile-matter data and permit determination of fixed carbon by difference under the applicable method [47].

Gross calorific value should be measured directly by bomb calorimetry using an appropriate standard method such as ASTM D5865/D5865M [48]. Where results are converted between analytical reporting bases, the conversion should use recognised procedures and only the variables actually available for the sample [49].

ISO 1928 provides an additional internationally recognised framework for determination of gross calorific value in solid mineral fuels [50].

These requirements are particularly important for QREC-MRT because the treatment hypothesis concerns changes that may be comparable in magnitude with natural between-sample variation if sampling and compositional equivalence are not adequately controlled. A confirmatory experiment should therefore treat representative sampling, sample preparation, analytical methodology and chain of

custody as integral parts of the treatment-effect model rather than as ancillary procedural details.

3.5 Primary Coal Endpoints

For the coal case study, the principal hypotheses may be expressed separately for analysis-sample moisture and gross calorific value.

Moisture hypothesis

- $H_{0,M}$**:** QREC-MRT does not produce a reduction in analysis-sample moisture beyond the corresponding change observed under the relevant comparison condition.
- $H_{1,M}$**:** QREC-MRT produces a greater reduction in analysis-sample moisture than the corresponding comparison condition.

For a treatment-control design:

$$\tau_M = \Delta\bar{M}_T - \Delta\bar{M}_C$$

A favourable treatment-associated moisture response requires:

$$\tau_M < 0$$

where a more negative value represents a greater reduction in moisture in the active-treatment condition relative to control.

Where a sham group is available:

$$\tau_{M,TS} = \Delta\bar{M}_T - \Delta\bar{M}_S$$

A treatment-specific interpretation would require the active-treatment response to remain distinguishable from both sham and untreated conditions.

Gross calorific-value hypothesis

- $H_{0,\mathrm{GCV}}$**:** QREC-MRT does not produce an increase in GCV beyond the corresponding change observed under the relevant comparison condition.
- $H_{1,\mathrm{GCV}}$**:** QREC-MRT produces a greater increase in GCV than the corresponding comparison condition.

For a treatment-control design:

$$\tau_{\mathrm{GCV}} = \Delta\overline{\mathrm{GCV}}_T - \Delta\overline{\mathrm{GCV}}_C$$

A favourable treatment-associated calorific-value response requires:

$$\tau_{\mathrm{GCV}} > 0$$

Where a sham group is available:

$$\tau_{GCV,TS} = \Delta GCV_T - \Delta GCV_S$$

For the present coal dataset, the available analysis is a paired before-and-after comparison rather than a treatment-control difference-in-differences analysis. Absolute and relative changes are therefore reported directly from the laboratory measurements, and no treatment-specific causal contrast can be estimated from the present pair alone.

3.6 Multidomain Extension of the Quantitative Framework

QREC-MRT is intended as a multidomain technology platform. The quantitative framework developed above is therefore not limited to coal, although each application domain requires its own scientifically appropriate endpoint, analytical method, comparison condition, and uncertainty model.

The general response formulation remains:

$$\Delta Y_i = Y_{i,\text{post}} - Y_{i,\text{pre}}$$

with the corresponding normalised response:

$$R_i = \left(\frac{Y_{i,\text{post}} - Y_{i,\text{pre}}}{Y_{i,\text{pre}}}\right) \times 100$$

and, where controls are available:

$$\hat{\tau} = \Delta Y_T - \Delta Y_C$$

The variable Y is domain-specific:

- Solid fuels: Y may represent GCV, moisture, ash, or another prespecified fuel characteristic.
- Liquid fuels: Appropriate endpoints may include directly measured heat of combustion, composition, density, viscosity, or other relevant fuel properties.
- Gaseous fuels: Endpoints may derive from measured gas composition and independently calculated calorific properties.
- Photovoltaic systems: Y should represent a performance measure corrected for relevant environmental variables such as irradiance, module temperature, and system availability.
- Agricultural applications: The endpoint should be defined prospectively and may comprise a physiological, growth, productivity, or resource-use variable.
- Biological-response studies: Physical exposure variables and biological endpoints should be treated separately so that a measured biological response is not automatically interpreted as evidence of a change in the physical exposure itself.

The quantitative structure is therefore transferable, but the scientific meaning of Y, the relevant comparison condition, and the minimum practically meaningful effect must be defined independently for each domain.

The present manuscript does not use these other domains as evidence for the coal findings. Their inclusion here establishes the generality of the validation architecture rather than equivalence of the available empirical evidence across applications.

3.7 Application of the Evidentiary Framework Across Domains

The evidentiary hierarchy defined in Section 3.2 is applicable across QREC-MRT domains irrespective of the physical endpoint selected. The domain-specific variable
, comparison condition, analytical method and uncertainty structure may differ, but progression from analytical observation to reproducibility, controlled treatment association and mechanism remains unchanged. The present coal case study is treated primarily as Level 1 evidence, while the confirmatory design described later is intended to test progression toward Levels 2 and 3**.**

4. Materials and Methods

4.1 Study Design

This study combines a quantitative and physics-informed evaluation framework for QREC-MRT with retrospective analysis of independent laboratory measurements from a coal application.

The empirical component is based on paired SGS India Private Limited analytical reports corresponding to coal specimens identified as before and after QREC-MRT intervention.

The analysis was restricted to parameters directly reported in the laboratory certificates. No numerical values were inferred for variables that were not measured.

The present empirical component should be distinguished from a prospective controlled efficacy experiment. The laboratory measurements provide analytical values for the two submitted specimens. In this paper, those values are used to quantify the observed between-specimen differences and to define numerical endpoints for subsequent controlled replication.

The coal case study therefore serves two purposes: first, to demonstrate application of the quantitative response calculations developed in Section 3; and second, to define the experimental limitations that must be addressed before treatment-specific inference can be made.

4.2 Coal Analytical Dataset

The before-intervention coal specimen was identified by SGS as “COAL BEFORE ENERGY BROADCAST” under Sample/Report No. CG25-002994.002.

The corresponding after-intervention specimen was identified as “COAL AFTER ENERGY BROADCAST” under Sample/Report No. CG25-002994.005.

Both specimens were registered by SGS on 6 February 2025, and both reports were issued on 25 February 2025. The product group was recorded as Solid Fuels, with an approximate submitted quantity of 250 g per specimen.

Three directly comparable analytical outcomes were available:

1. gross calorific value on an air-dry basis;
2. gross calorific value on a dry basis; and
3. moisture in the analysis sample on an air-dry basis.

Gross calorific value was determined using ASTM D5865/D5865M-19 [48]. Analysis-sample moisture was determined using ASTM D3173/D3173M-17a [45].

No additional compositional values are inferred in this paper from parameters not contained in the corresponding SGS reports.

4.2.1 Evidentiary Status of the Coal Dataset

The available dataset consists of one before-labelled and one after-labelled coal specimen submitted for independent laboratory analysis. The measurements therefore establish the analytical properties reported by SGS for these two specimens.

The dataset does not include an untreated contemporaneous control, sham condition, randomised treatment allocation, blinded treatment assignment or independently prepared replicate treatment and comparison units.

The laboratory certificates also do not, by themselves, establish complete equivalence of the coal portions before intervention or document the entire pre-laboratory sequence of parent-stock sampling, homogenisation, subdivision, custody transfers and transport.

These limitations restrict causal inference from the present pair but do not alter the numerical laboratory measurements themselves. The measured values are therefore treated as observational endpoints for application of the quantitative framework rather than as a controlled estimate of QREC-MRT efficacy.

The direction and magnitude of the observed differences can nevertheless be stated precisely and can be used to define prespecified endpoints for a prospective active-sham-control experiment.

4.3 Data Extraction and Verification

Numerical values were transcribed directly from the SGS laboratory certificates. For each parameter, the before-intervention value, after-intervention value, analytical unit and reporting basis were retained as reported.

The primary dataset comprised:

- GCV, air-dry basis: 4,057 and 5,160 kcal/kg
- GCV, dry basis: 4,122 and 5,206 kcal/kg
- Moisture, air-dry basis: 1.57% and 0.88% w/w

The analytical bases reported by SGS were preserved. Analysis-sample moisture was not relabelled as total moisture, inherent moisture or as-received moisture.

No adjustment was made for ash, mineral matter, volatile matter, fixed carbon or elemental composition because corresponding paired measurements were not available in the present laboratory reports.

4.4 Calculation of Observed Change

For each measured parameter, the absolute between-specimen change was calculated as:

$$\Delta Y = Y_{\text{after}} - Y_{\text{before}}$$

where:

- Y_{before} = measured value in the before-intervention specimen;
- Y_{after} = measured value in the after-intervention specimen.

Relative change was calculated as:

$$R_Y = \left(\frac{Y_{\text{after}} - Y_{\text{before}}}{Y_{\text{before}}}\right) \times 100$$

For moisture, the absolute difference is expressed in percentage points, while the relative difference is expressed as a percentage of the before-intervention value.

For GCV, absolute change in kcal/kg and relative percentage change were calculated independently on the air-dry and dry analytical bases.

For the present paired dataset, these quantities represent observed between-specimen differences rather than estimates of a controlled treatment effect. A treatment-specific contrast such as τ_{TC} or τ_{TS}, defined in Section 3, cannot be calculated because contemporaneous control and sham groups were not available.

4.5 Interpretation of Dry-Basis GCV

Dry-basis GCV was examined as a complementary endpoint because conversion to a dry basis removes the direct contribution of measured analysis-sample moisture to sample mass.

The observed relative differences were:

$$R_{\text{GCV,air-dry}} = +27.20\%$$

and:

$R_{GCV,dry} = +26.30\%$

The difference between the two relative responses was therefore:

$$27.20 - 26.30 = 0.90 \text{ percentage points}$$

Analysis-sample moisture was determined using the recognised coal-moisture method identified in the SGS report [45]. Ash is also relevant to interpretation of calorific value because mineral matter contributes to sample mass while contributing differently to combustible energy [46]. A complete proximate analysis would additionally provide information on moisture, ash, and volatile matter and permit determination of fixed carbon by difference under the applicable procedure [47].

Gross calorific value was determined independently using the bomb-calorimetric method identified in the SGS laboratory certificates [48]. Conversion between analytical reporting bases should be carried out using recognised procedures [49], while ISO 1928 provides an additional internationally recognised framework for calorific-value determination in solid mineral fuels [50].

The persistence of most of the observed GCV difference after conversion to a dry basis shows that the measured difference in analysis-sample moisture alone cannot mathematically account for the calorific-value difference between the two specimens.

Dry-basis normalisation does not, however, establish equivalence of the underlying dry coal fractions. Differences in ash, mineral matter, maceral composition, volatile matter, fixed carbon, elemental composition, or sampling provenance can also influence dry-basis calorific value.

The dry-basis GCV result is therefore treated as a separate quantitative endpoint. Controlled replication with representative sampling and paired compositional measurements is required to determine whether a comparable dry-basis response is reproducibly associated with QREC-MRT.

4.6 Statistical Approach

The available empirical dataset contains one before-intervention and one after-intervention coal specimen. Statistical analysis is therefore descriptive rather than inferential.

The results are reported using:

1. measured before-intervention values;
2. measured after-intervention values;
3. absolute between-specimen difference;
4. relative percentage difference; and

5. comparison between air-dry and dry-basis GCV responses.

No p-values, confidence intervals or estimates of between-unit variance were calculated because the available dataset contains no independent experimental replicates from which those quantities could be estimated reliably.

The present calculations therefore describe the magnitude and direction of the observed analytical differences. They do not estimate a population-level treatment effect.

Under the quantitative framework developed in Section 3, inferential analysis becomes appropriate when independently prepared active, sham and untreated experimental units are available. Such a design would permit estimation of treatment contrasts, uncertainty and reproducibility.

4.7 Data Presentation

The coal results are presented using two summary tables and four quantitative figures.

Table 1 identifies the laboratory reports, sample descriptions, analytical methods and associated metadata.

Table 2 presents the before-intervention and after-intervention values together with absolute and relative differences.

Figures 3 and 4 display the air-dry and dry-basis GCV measurements, respectively. **Figure 5** presents the corresponding analysis-sample moisture measurements, while **Figure 6** compares the three observed relative differences on a common
percentage-change scale.

All derived numerical values were calculated directly from the measurements reported in the SGS certificates. No unmeasured compositional variable was estimated or inserted into the quantitative analysis.

5. Results

5.1 Coal Analytical Dataset

The empirical case study comprised two coal reports issued by SGS India Private Limited. The before-intervention specimen was identified as “COAL BEFORE ENERGY BROADCAST” under Sample/Report No. CG25-002994.002, and the after-intervention specimen as “COAL AFTER ENERGY BROADCAST” under Sample/Report No. CG25-002994.005.

Both reports were issued on 25 February 2025.

Three directly comparable analytical parameters were available:

1. gross calorific value on an air-dry basis;

2. gross calorific value on a dry basis; and
3. moisture in the analysis sample on an air-dry basis.

Table 1. SGS analytical reports included in the study

Characteristic	Before intervention	After intervention
SGS Sample/Report No.	CG25-002994.002	CG25-002994.005
Sample description	COAL BEFORE ENERGY BROADCAST	COAL AFTER ENERGY BROADCAST
Product group	Solid Fuels	Solid Fuels
Approx. submitted quantity	250 g	250 g
Report issue date	25 February 2025	25 February 2025
GCV method	ASTM D5865/D5865M-19	ASTM D5865/D5865M-19
Moisture method	ASTM D3173/D3173M-17a	ASTM D3173/D3173M-17a

5.2 Comparative Analytical Results

All three measured parameters differed between the before-intervention and after-intervention specimens in the direction specified by the QREC-MRT coal hypothesis.

Air-dry GCV increased from 4,057 to 5,160 kcal/kg. Dry-

basis GCV increased from 4,122 to 5,206 kcal/kg.

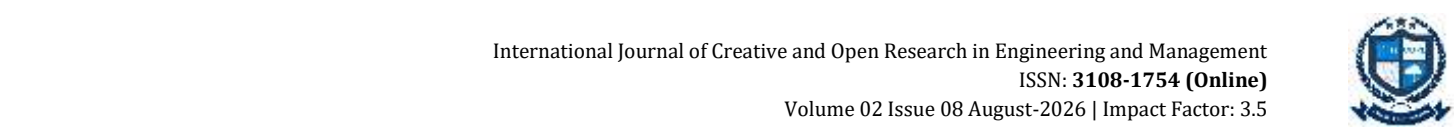
Analysis-sample moisture decreased from 1.57% to 0.88% w/w.

Table 2. Before- and after-intervention coal analytical results

Parameter	Before	After	Absolute difference	Relative difference
GCV, air-dry basis (kcal/kg)	4,057	5,160	+1,103	+27.20%
GCV, dry basis (kcal/kg)	4,122	5,206	+1,084	+26.30%
Moisture, air-dry basis (% w/w)	1.57	0.88	−0.69 pp	−43.95%

pp = percentage points.

5.3 Gross Calorific Value Response



Gross calorific value on an air-dry basis differed by +1,103 kcal/kg:

$$\Delta GCV_{air\text{-}dry} = 5{,}160 - 4{,}057 = +1{,}103 \text{ kcal/kg The}$$

corresponding relative difference was:

$$R_{GCV,air\text{-}dry} = \left(\frac{1{,}103}{4{,}057}\right) \times 100 = +27.20\%$$

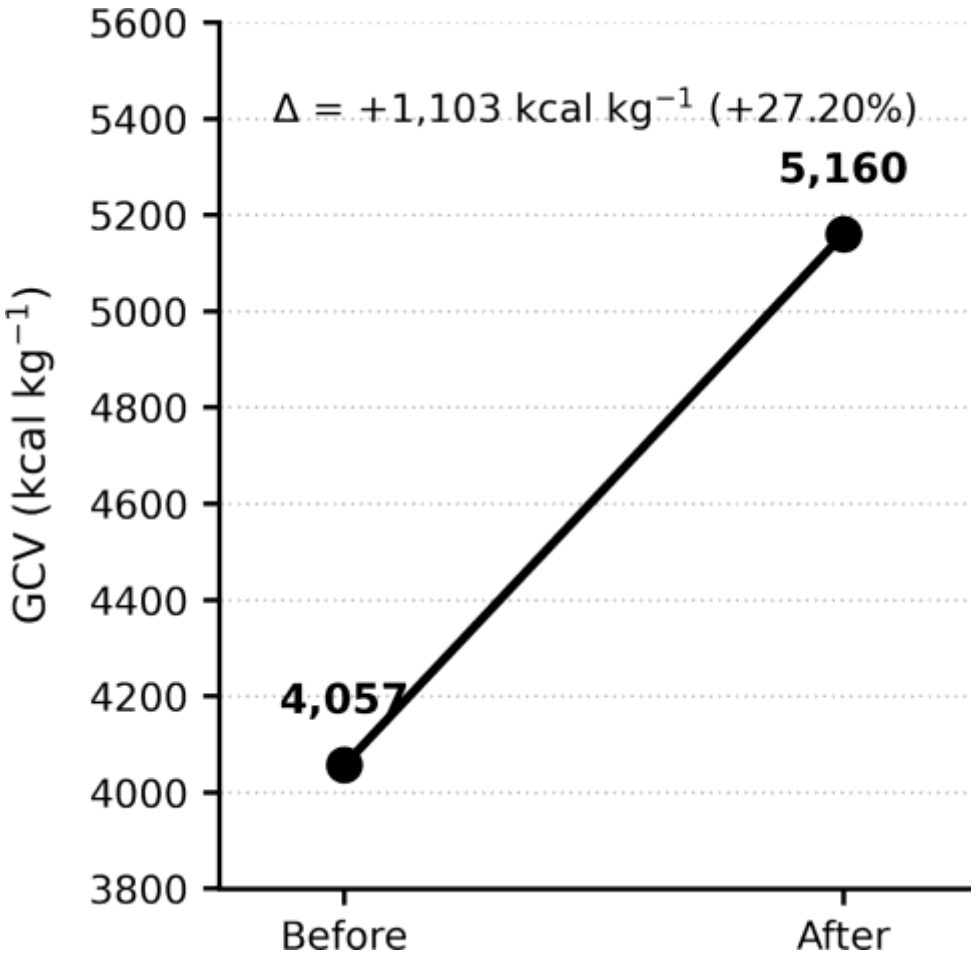


Figure 3. Gross calorific value of the before-intervention and after-intervention coal specimens on an air-dry basis. GCV was 4,057 and 5,160 kcal/kg, respectively, corresponding to an absolute difference of +1,103 kcal/kg and a relative difference of +27.20%.

On a dry basis, the absolute GCV difference was +1,084 kcal/kg:

$$\Delta GCV_{dry} = 5{,}206 - 4{,}122 = +1{,}084 \text{ kcal/kg The}$$

corresponding relative difference was:

$$R_{GCV,dry} = \left(\frac{1{,}084}{4{,}122}\right) \times 100 = +26.30\%$$

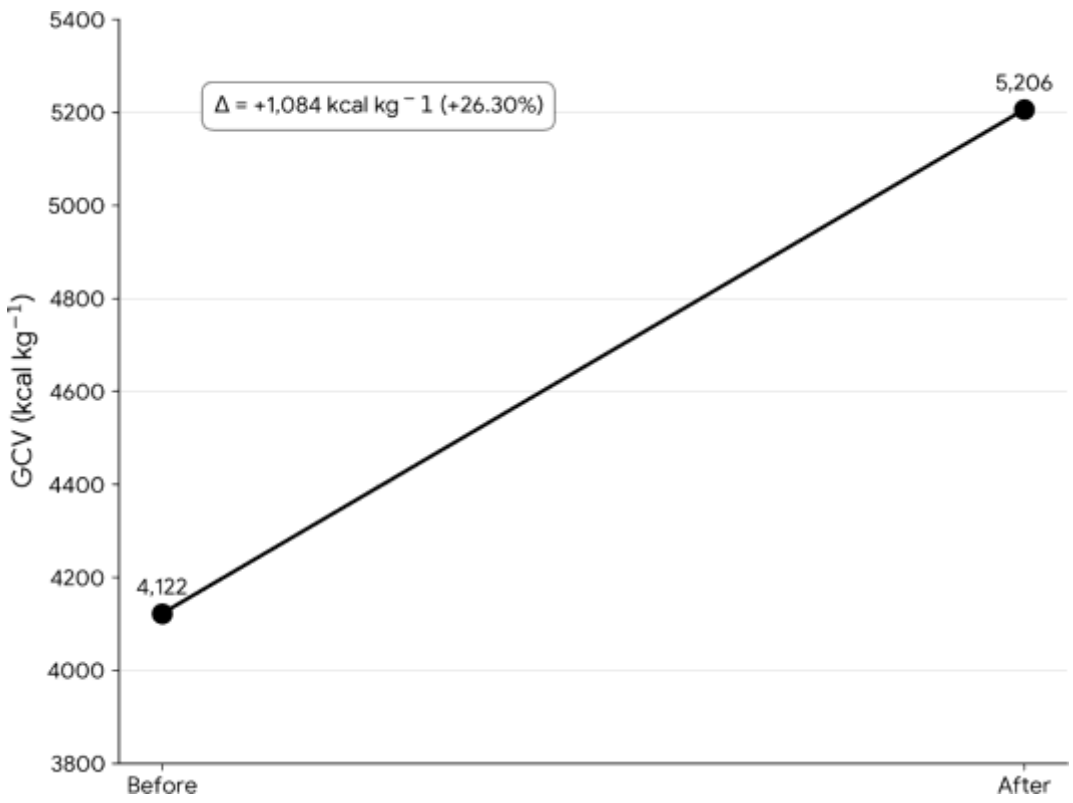


Figure 4. *Gross calorific value of the before-intervention and after-intervention coal specimens on a dry basis. GCV was 4,122 and 5,206 kcal/kg, respectively, corresponding to an absolute difference of +1,084 kcal/kg and a relative difference of +26.30%.*

The relative GCV differences on the two analytical bases were similar. Conversion from an air-dry to a dry basis changed the relative difference by only 0.90 percentage points, from +27.20% to +26.30%.

5.4 Moisture Response

Moisture in the analysis sample decreased from 1.57% to 0.88% w/w. $\Delta M = 0.88 - 1.57 = -0.69$ percentage points

The relative change was:

$$\text{Relative moisture change} = [(0.88 - 1.57) / 1.57] \times 100$$

$$= -43.95\%$$

The after-intervention sample therefore contained approximately 44% less analysis-sample moisture relative to the baseline value.

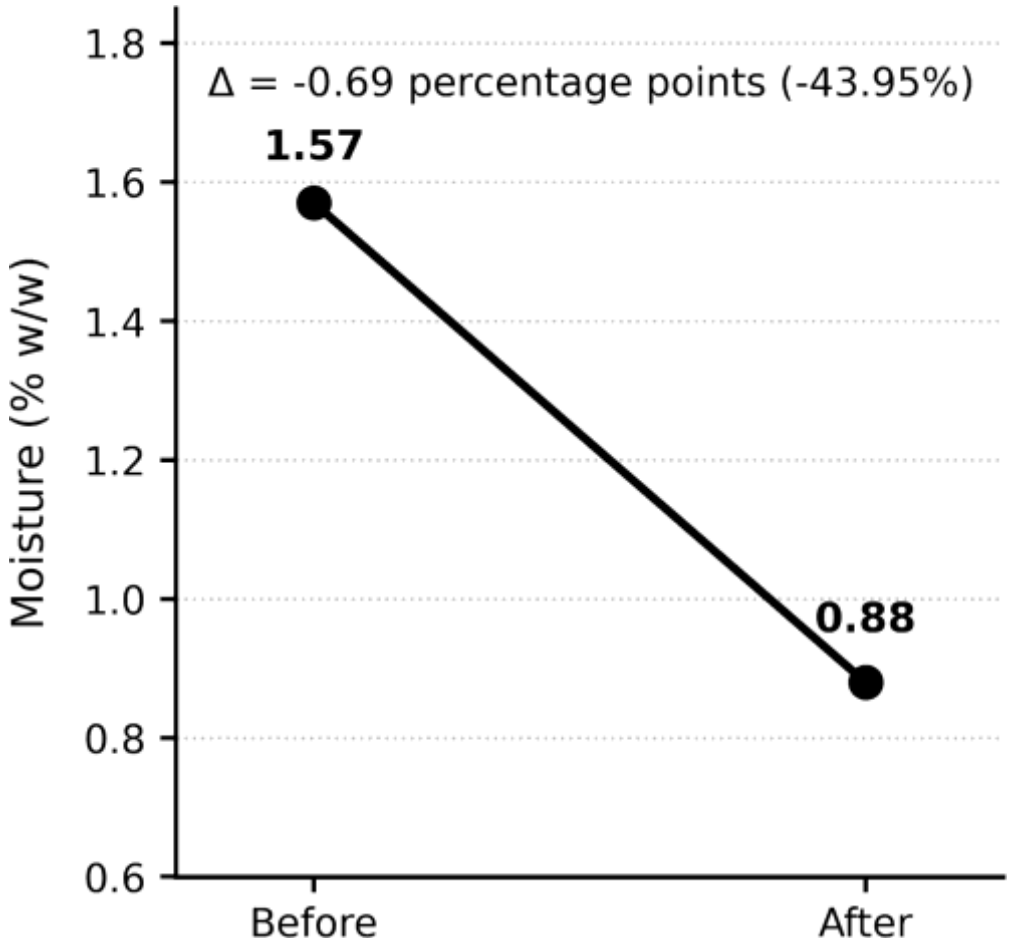


Figure 5. Moisture in the analysis sample of the before-intervention and after-intervention coal specimens. Moisture was 1.57% and 0.88% w/w, respectively, corresponding to an absolute difference of −0.69 percentage points and a relative difference of −43.95%.

The terminology "moisture in the analysis sample" is retained because this is the parameter reported by SGS and should not be interpreted as total or as-received moisture.

5.5 Normalised Comparison of Measured Responses

The relative differences in the three measured parameters were:

$R_{GCV,air\text{-}dry} = +27.20\%$

$R_{GCV,dry} = +26.30\%$

$R_M = -43.95\%$

Figure 6 displays these outcomes on a common percentage-change scale. The purpose of the normalisation is to compare the magnitude and direction of the

measured differences without combining variables expressed in different physical units.

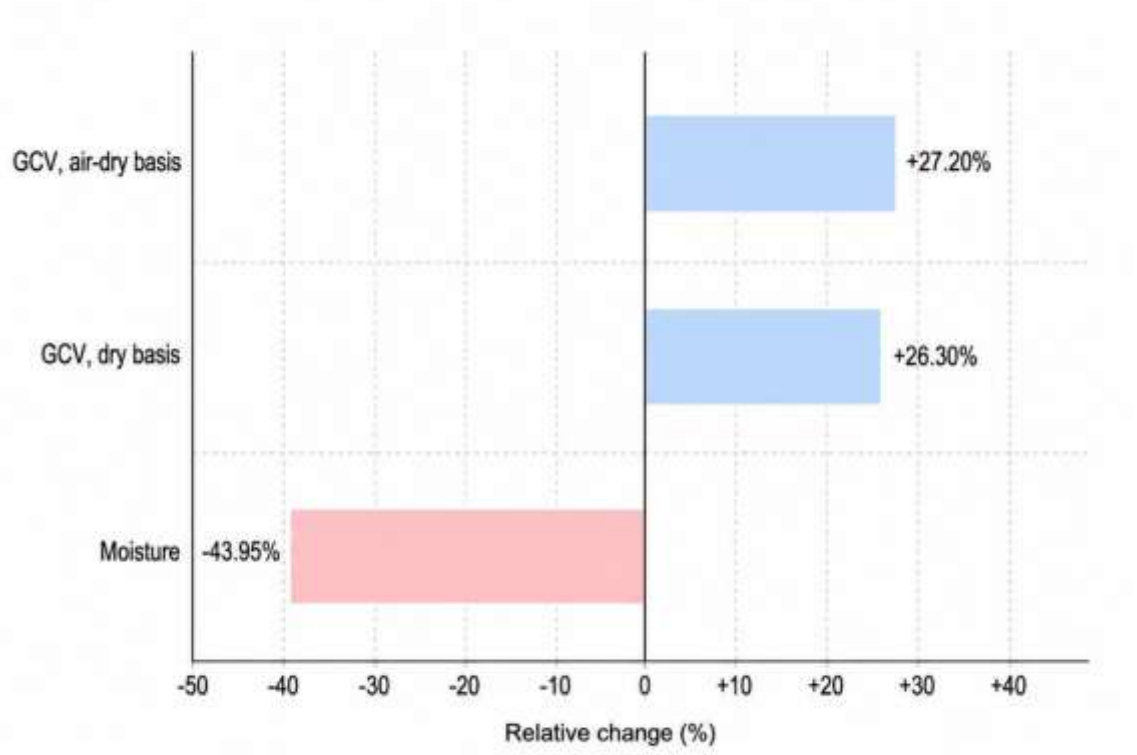


Figure 6. *Normalised relative differences in measured coal parameters between the before-intervention and after-intervention specimens. Positive values indicate higher after-intervention values and negative values indicate lower after-intervention values relative to baseline.*

The similarity between the air-dry and dry-basis GCV differences is the main internal feature of this comparison. If the air-dry difference arose predominantly from the measured reduction in analysis-sample moisture, a much smaller relative difference would be expected after conversion to a dry basis. Instead, dry-basis GCV remained 26.30% higher in the after-intervention specimen.

This observation does not identify the cause of the GCV difference. It shows only that the measured analysis-sample moisture difference is insufficient, by itself, to account mathematically for the observed calorific-value difference.

5.6 Summary of Coal Case-Study Measurements

The paired coal analyses produced three quantitative observations:

1. air-dry GCV was **27.20% higher** in the after-intervention specimen;
2. dry-basis GCV was **26.30% higher**; and

3. analysis-sample moisture was **43.95% lower** relative to the before-intervention specimen.

All three differences are in the direction specified by the QREC-MRT coal hypothesis.

The similarity between the air-dry and dry-basis GCV differences shows that most of the measured GCV difference persisted after moisture normalisation. The measured difference in analysis-sample moisture therefore cannot, on its own, account for the observed calorific-value difference.

These results describe the two submitted specimens. They do not estimate a controlled QREC-MRT treatment effect because the available dataset contains no contemporaneous untreated group, sham condition or independent replicate experimental units.

Their role in the present study is to provide quantitative observational endpoints against which subsequent controlled QREC-MRT experiments can be designed and evaluated.

6. Quantitative Interpretation and Discussion

6.1 Principal Findings

The coal case study produced three measured between-specimen differences in the direction specified by the QREC-MRT coal hypothesis. Air-dry GCV was 27.20% higher in the after-intervention specimen, dry-basis GCV was 26.30% higher, and analysis-sample moisture was 43.95% lower relative to the corresponding before-intervention value.

The similarity between the air-dry and dry-basis GCV differences is relevant to interpretation. Conversion to a dry basis changed the relative GCV difference by only
0.90 percentage points. The measured difference in analysis-sample moisture therefore accounts for only part of the observed difference in the energetic characteristics of the two specimens.

The present dataset does not determine what proportion of the observed difference, if any, is specifically attributable to QREC-MRT. It does, however, define three quantitative endpoints that can be tested prospectively under controlled conditions.

Within the evidentiary framework developed in Section 3, the present coal dataset is therefore treated primarily as an analytical observation rather than as a controlled treatment-effect estimate.

6.2 Significance of the Dry-Basis GCV Difference

Gross calorific value represents the heat released during complete combustion of a specified mass of fuel under defined conditions. Standardised bomb-calorimetric

determination provides a direct measure of the energetic characteristic of the tested coal specimen [48].

The measured dry-basis values were:

$$GCV_{before,dry} = 4{,}122 \text{ kcal/kg } GCV_{after,dry}$$

$$= 5{,}206 \text{ kcal/kg}$$

The corresponding ratio was:

$$\frac{5{,}206}{4{,}122} = 1.263$$

The after-intervention specimen therefore exhibited a dry-basis GCV approximately 1.263 times the before-intervention value. The

air-dry ratio was:

$$\frac{5{,}160}{4{,}057} = 1.272$$

The similarity between the two ratios shows that most of the measured GCV difference remained after removal of the direct contribution of analysis-sample moisture.

This does not imply that moisture is unimportant. Analysis-sample moisture differed by −43.95% between the two specimens. Rather, the paired results contain two analytically distinct observations: lower measured moisture and a GCV difference that remains largely present on a dry basis.

The dry-basis comparison therefore provides an important numerical endpoint for subsequent controlled replication.

6.3 Coal Heterogeneity and Possible Material Basis

Coal is intrinsically heterogeneous. Different portions of the same nominal coal stock may vary in combustible organic matter, mineral content, maceral composition and other constituents unless representative sampling and controlled sample preparation are used [41,42].

The present laboratory reports establish the properties measured in the submitted specimens. They do not, by themselves, establish that the before-intervention and after-intervention portions originated from statistically equivalent subdivisions of a homogenised parent coal lot.

This issue is particularly relevant when interpreting calorific value. Ash and mineral matter contribute to sample mass without contributing equivalently to combustible

energy. Paired ash measurements should therefore be included in future QREC-MRT coal experiments [46].

Complete proximate analysis would provide additional information on moisture, ash and volatile matter and permit determination of fixed carbon under the applicable procedure [47]. Where sufficient data are available, conversion between analytical bases can further assist interpretation of differences among coal specimens [49].

If a comparable QREC-MRT-associated GCV response is reproduced under controlled sampling conditions, structural and compositional characterisation should follow. FTIR spectroscopy could examine changes in functional-group environments, Raman spectroscopy could assess carbon ordering, X-ray diffraction could examine structural organisation, and thermal analysis could evaluate changes in decomposition behaviour.

These measurements should complement rather than replace calorimetry. The primary question in a confirmatory experiment remains whether the prespecified GCV and moisture responses are reproduced preferentially in the active-treatment condition.

6.4 Scientific Interpretation in Relation to QREC-MRT

The three measured coal parameters changed in the direction specified by the QREC-MRT coal hypothesis. Interpretation must nevertheless recognise the effect of coal sampling and preparation on analytical comparability. Representative sampling and controlled preparation are therefore essential when differences between coal portions are evaluated [41,42].

Analysis-sample moisture can influence calorific value when results are expressed on a moisture-containing basis. The moisture measurements reported in the present case study were determined using the applicable analytical method [45].

Dry-basis normalisation removes the direct contribution of measured moisture but does not remove possible differences in ash or mineral matter. Ash therefore remains an important complementary variable when calorific-value differences are evaluated [46].

A complete proximate analysis would provide additional compositional information and permit fixed-carbon determination by difference under the relevant procedure [47]. Such measurements should be obtained concurrently in future controlled QREC-MRT coal trials.

Gross calorific value in the present specimens was determined using the recognised bomb-calorimetric method identified in the laboratory certificates [48]. The measured differences were +27.20% on an air-dry basis and +26.30% on a dry basis.

Conversion between analytical reporting bases provides a recognised method for examining the effect of moisture and other reporting variables on coal-analysis

results [49]. In the present case, conversion to a dry basis changed the relative GCV difference by only 0.90 percentage points.

ISO 1928 provides an additional internationally recognised framework for determination of gross calorific value in solid mineral fuels [50]. Within these analytical boundaries, the after-intervention specimen differed from the before-intervention specimen in both measured moisture and energetic characteristics.

The current pair cannot establish that QREC-MRT caused these differences because the required contemporaneous controls and independent replicates are absent. The measurements nevertheless provide numerical endpoints for evaluating whether the same directional pattern can be reproduced under a prospective active-sham-control design.

If the response is reproduced consistently in active-treatment units and remains distinguishable from both sham and untreated comparison units, the evidence would progress from the present analytical-observation level toward a controlled treatment association. Mechanism-specific investigation should then determine the physical or material pathway associated with that response.

6.5 Implications for Further QREC-MRT Development

The present coal measurements provide a quantitative starting point for the next experimental phase. A confirmatory coal programme should test whether three features are reproduced:

- reduction in analysis-sample moisture;
- increase in air-dry GCV; and
- persistence of the GCV difference after conversion to a dry basis.

The numerical values observed in the present case study provide reference endpoints:

$R_{\mathrm{GCV,air\text{-}dry}} = +27.20\%$

$R_{\mathrm{GCV,dry}} = +26.30\%$

$R_M = -43.95\%$

These values should not be treated as assumed effect sizes for all future coal experiments. Their role is to provide empirical benchmarks against which subsequent independent measurements can be compared.

QREC-MRT is not limited to coal. The same quantitative validation logic can be applied to other application domains, but the endpoint Y, relevant control condition, analytical uncertainty, and minimum practically meaningful response must be defined separately for each domain.

Accordingly, the broader development programme should distinguish platform applicability from domain-specific evidence. A response observed in one application does not establish efficacy in another. Each domain requires its own controlled experimental evidence.

7. Limitations and Evidentiary Boundaries

The empirical coal component consists of one before-labelled and one after-labelled specimen analysed independently by SGS India Private Limited. The dataset permits direct quantitative comparison of these specimens but does not provide independent experimental replicates from which reproducibility or population-level treatment effects can be estimated.

No untreated contemporaneous control, sham condition, randomised allocation or blinded treatment assignment was available. The observed between-specimen differences therefore cannot be separated statistically from all potential effects of sampling variation, handling differences or other uncontrolled variables.

Coal heterogeneity is an important consideration. Specimens from the same nominal stock may differ in mineral matter, ash, maceral distribution, volatile matter, fixed carbon and elemental composition unless the parent material is appropriately homogenised and subdivided. The available documentation does not establish complete pre-intervention equivalence of the two submitted coal portions.

The laboratory reports establish the analytical measurements made after receipt of the specimens, but they do not provide a complete pre-laboratory chain-of-custody record covering parent-stock identification, sampling, homogenisation, subdivision, handling and transport. These procedures should be documented prospectively in a confirmatory experiment.

Conversion to a dry basis shows that the measured difference in analysis-sample moisture alone cannot account mathematically for the GCV difference. Dry-basis normalisation does not, however, correct for possible differences in ash, mineral matter or combustible composition. Paired ash, complete proximate analysis and ultimate analysis were not available in the present dataset.

The absence of independent experimental replicates also means that within-group variance, confidence intervals and treatment-effect uncertainty cannot be estimated. The reported percentage differences therefore describe the two analysed specimens and should not be interpreted as an expected response magnitude across coal populations.

The physical coupling pathway of QREC-MRT remains under investigation. Photographs, geographic coordinates and associated metadata are used within the operational protocol to identify and distinguish the intended target; they are not presented as the physical transmission mechanism. The coal measurements

address the observable analytical response rather than the physical coupling pathway.

These limitations define the evidentiary level of the present case study. They do not alter the measured values themselves. The appropriate next step is therefore prospective controlled replication using representative sampling, independent experimental units and prespecified active, sham and untreated comparison conditions.

8. Multidomain Quantitative Validation Framework

QREC-MRT is intended as a multidomain technology platform. The purpose of this section is not to claim equivalent experimental evidence across all proposed applications, but to show how the quantitative validation model developed in this paper can be adapted to different physical and biological endpoints.

The underlying structure remains common across domains:

$$\Delta Y_i = Y_{i,\text{post}} - Y_{i,\text{pre}}$$

$$R_i = \left(\frac{Y_{i,\text{post}} - Y_{i,\text{pre}}}{Y_{i,\text{pre}}} \right) \times 100$$

and, where comparison groups are available:

$$\tau_{TC} = \Delta \bar{Y}_T - \Delta \bar{Y}_C$$

$$\tau_{TS} = \Delta \bar{Y}_T - \Delta \bar{Y}_S$$

8.1 Liquid- and Gaseous-Fuel Applications

Where QREC-MRT is evaluated in liquid fuels, representative sampling should precede intervention and analysis so that the tested portions remain representative of the parent fuel batch [51]. Density should be measured at a specified temperature because temperature-dependent variation can influence comparison of liquid-fuel properties [52].

Where viscosity forms part of the treatment hypothesis, kinematic viscosity should be determined using an appropriate standard method [53]. Flash point should likewise be measured using a recognised procedure where changes in volatility or fuel-handling characteristics are relevant [54].

If the principal endpoint concerns energy content, heat of combustion should be measured directly rather than inferred from secondary properties. Established bomb-calorimetric methods provide appropriate procedures for such measurements [55,56].

For gaseous fuels, representative sampling is similarly necessary because measured composition can depend on sampling procedure, pressure and system configuration [57]. Composition should be determined directly using a suitable chromatographic method [58].

Measured gas composition may then be used to derive calorific value, density, relative density and Wobbe Index according to established procedures [59].
Interpretation should consider the wider fuel-property profile because improvement in one parameter does not necessarily imply overall improvement in operational suitability [60].

The purpose of these methods within the present framework is to define how a future QREC-MRT fuel response should be measured. No liquid- or gaseous-fuel efficacy conclusion is drawn from the coal dataset reported in this paper.

8.2 Photovoltaic and Energy-System Applications

For photovoltaic applications, raw electricity generation should not be used in isolation as a treatment endpoint because irradiance, temperature, system availability and monitoring quality can materially influence measured output. Recognised photovoltaic monitoring principles provide a basis for controlling these variables [61].

Power-performance and capacity evaluation may use an established performance-index methodology, while longer-term evaluation should distinguish measured energy production from expected production under corresponding environmental conditions [62,63].

Performance ratio and related normalised indicators provide established approaches for comparing grid-connected photovoltaic systems under varying operating conditions [64]. Module temperature should also be measured because operating temperature directly affects electrical performance [65].

Soiling is another potential confounder because dust accumulation, rainfall and cleaning can alter photovoltaic output independently of any intervention [66].

A confirmatory QREC-MRT photovoltaic experiment should therefore compare matched systems or use an appropriate crossover design, prespecify the primary performance endpoint and correct for the principal environmental variables.

The validation principle is the same as for coal: a measured change becomes evidence of treatment association only when it is reproducible and distinguishable from appropriate comparison conditions.

8.3 Agricultural and Plant-Physiology Applications

Agricultural QREC-MRT studies should use prespecified physiological, growth or productivity endpoints rather than relying primarily on visual assessment. Chlorophyll

fluorescence provides an established method for evaluating photosynthetic function when measurements are obtained under controlled conditions [67,68].

Additional fluorescence parameters can provide information on photosystem II redox state and excitation-energy distribution where photosynthetic performance is a primary endpoint [69].

Plant experiments should control positional, nutritional, irrigation, container and other environmental effects because apparently small differences in growth conditions can alter physiological and biomass outcomes [70].

Phenotyping datasets should retain adequate metadata to permit interpretation and reuse [71]. Where water-use efficiency is evaluated, the measurement scale and calculation method should be specified because leaf-, plant- and crop-level measures are not interchangeable [72].

Emerging agricultural water-management technologies illustrate the importance of relating measured water-use responses to the crop and production system being studied [73]. Environmental sensor networks can further provide continuous measurements of variables such as temperature, humidity, soil condition and plant microenvironment [74].

Accordingly, the endpoint in an agricultural QREC-MRT experiment should be defined prospectively and evaluated against environmental and biological variability using appropriate comparison plots or experimental units.

8.4 Biological Stress and Microbiome Applications

Where QREC-MRT is investigated in relation to biological stress, biochemical endpoints should be interpreted in functional context. Reactive oxygen species, for example, participate in both cellular damage and signalling and should not be treated simply as undesirable variables whose reduction is automatically beneficial [75].

Plant-associated microbial communities likewise depend on interactions among the host, soil and surrounding environment [76]. Soil microbiomes participate in broader ecosystem functions, and community diversity alone is therefore insufficient to demonstrate a beneficial treatment response [77].

Where microbiome modification is proposed, changes should be linked to functional outcomes such as nutrient acquisition, disease suppression, plant growth or stress tolerance [78]. Root, soil and microbial communities should be considered as an interacting system rather than as isolated abundance measurements [79].

For these applications, QREC-MRT validation should therefore distinguish a statistically detectable biological difference from a biologically meaningful functional response.

8.5 Radiation and Space-Agriculture Applications

Radiation-related QREC-MRT studies require a clear distinction between a change in the physical radiation field and a change in biological response under the same measured exposure. Plant responses to ionising radiation depend on radiation quality, dose, dose rate and biological condition [80,81].

For space-agriculture applications, radiation exposure must additionally be considered within the wider requirements of cultivation in bioregenerative life-support systems [82].

Controlled irradiation experiments show the value of combining morphological measurements with physiological indicators rather than relying on growth alone [83].

Space cultivation also involves interacting constraints in plant physiology, environmental control and resource availability [84]. Nutrient accounting, including nitrogen management, is correspondingly important in closed or semi-closed agricultural systems [85].

A future QREC-MRT radiation experiment should therefore measure physical dose independently and evaluate biological protection as a separate endpoint. An observed biological benefit should not be interpreted automatically as evidence that the incident radiation field itself has changed.

8.6 Data Integrity, Digital Representation and Target Traceability

All confirmatory QREC-MRT studies should preserve raw measurements, sample identities, intervention records, analytical certificates, allocation information and derived calculations in a traceable research record. Where practicable, research data should follow the FAIR principles of findability, accessibility, interoperability and reusability [86].

Digital models may assist with baseline prediction, environmental correction and anomaly detection, but a distinction should be maintained between a static digital representation and a dynamically linked digital twin [87].

Large observational datasets can be integrated with continuously updated modelling frameworks to create digital representations of complex physical systems [88].
Comparable approaches are being explored in agriculture, where sensor information and predictive models can follow the state of a production system over time [89].

For QREC-MRT, such digital methods may support experimental monitoring and data interpretation but should not substitute for direct measurement of the primary endpoint.

Where geographic coordinates are used to identify a target, the coordinate reference system, acquisition method, accuracy, timestamp and associated metadata should be recorded using an appropriate geospatial metadata framework such as ISO 19115-1 [90].

The role of these records is target identification, traceability and reproducibility. They are not treated as the physical mechanism by which QREC-MRT interacts with the target.

8.7 General Validation Sequence

The multidomain validation framework can be condensed into four stages.

Stage 1: Analytical replication

The prespecified response should first be reproduced in independently prepared experimental units. At this stage:

$$E_2 \Longrightarrow E_1$$

but reproducibility alone does not establish treatment specificity.

Stage 2: Controlled confirmation

Active QREC-MRT should be compared prospectively with appropriate untreated and, where feasible, sham conditions. The principal contrasts are:

$$\tau_{TC} = \Delta Y_T - \Delta Y_C$$

and:

$$\tau_{TS} = \Delta Y_T - \Delta Y_S$$

A treatment-associated interpretation requires the active condition to remain distinguishable from the relevant comparison conditions relative to the expected analytical and experimental variability.

Stage 3: Independent reproduction

The controlled response should then be tested by independent investigators, sites, or laboratories where practicable. Reproduction across independent experimental settings provides stronger evidence of generalisability than repeated measurements within a single experimental system.

Stage 4: Mechanistic characterisation

Only after a controlled response is reproduced should the primary endpoint be combined with measurements designed specifically to test competing physical, chemical, structural, or biological mechanisms.

The evidentiary progression is therefore:

$$E_1 \rightarrow E_2 \rightarrow E_3 \rightarrow E_4$$

without assuming that evidence at one level automatically establishes the next.

This structure allows QREC-MRT to retain its multidomain scope while requiring each application to establish its own evidentiary progression independently.

8.8 Minimum Confirmatory Coal Experiment

Because coal provides the worked empirical case study in the present paper, a confirmatory coal experiment can be specified in greater detail.

The study should begin with a sufficiently large and representative parent coal lot. The material should be homogenised as far as practicable and divided into multiple coded experimental portions using a documented representative sampling and subdivision procedure.

Experimental units should then be allocated prospectively to:

- active QREC-MRT;
- sham intervention; and
- untreated control.

Randomised allocation should be used where operationally feasible.

Sample identities should be concealed from the analytical laboratory and, where practicable, from personnel responsible for post-intervention sample handling. The allocation key should remain inaccessible until laboratory measurements have been completed and the analytical dataset has been locked.

Each experimental condition should contain sufficient independent units to permit estimation of within-group variability.

For each unit, the principal endpoints should include:

- gross calorific value;
- analysis-sample moisture;
- ash;
- volatile matter;
- fixed carbon; and
- ultimate elemental composition.

GCV should be measured using replicate bomb-calorimetric determinations where appropriate.

For endpoint Y, the principal contrasts should be:

$$\tau_{TC} = \Delta\bar{Y}_T - \Delta\bar{Y}_C$$

and:

$$\tau_{TS} = \Delta\bar{Y}_T - \Delta\bar{Y}_S$$

A treatment-associated QREC-MRT response would require the active-treatment contrasts to be consistent with the prespecified directional hypothesis and distinguishable from analytical and between-sample variability.

For the principal coal endpoints, the expected directions are:

$\tau_{\mathrm{GCV}} > 0$

and:

$$\tau_M < 0$$

where positive τ_{GCV} represents a greater GCV increase in the active condition and negative τ_M represents greater moisture reduction.

Chain-of-custody documentation should record parent-lot identity, sampling procedure, homogenisation and subdivision, sample mass, coded identifiers, custody transfers, intervention timing, relevant environmental conditions, packaging, transport, and laboratory receipt.

The primary endpoints, minimum effect of interest, and statistical-analysis plan should be specified before treatment allocation is revealed.

If a reproducible active-treatment response remains distinguishable from both sham and untreated controls, subsequent studies should investigate the associated material pathway. FTIR, Raman spectroscopy, X-ray diffraction, and thermal analysis can then be applied to the same coded experimental units to determine whether the energetic response is accompanied by measurable compositional or structural changes.

Direct physical measurements should likewise be incorporated where they can test candidate coupling mechanisms.

Independent reproduction of the result would provide the basis for progressing from a controlled treatment association to mechanism-specific investigation.

9. Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors. The development of QREC-MRT and preparation of the present manuscript were undertaken independently by the author.

10. Declaration of Competing Interest

QREC-MRT was independently conceived and developed by the author, Dr Reji Kurien Thomas. The author has an intellectual-property and professional interest in QREC-MRT and discloses this relationship in the interest of transparency.

TOL Biotech was not involved in the invention or development of QREC-MRT. SGS India Private Limited performed the analytical measurements used in the coal case study independently and had no role in the invention or development of QREC-MRT, interpretation of the results or preparation of this manuscript.

The identification of these interests does not alter the evidentiary framework adopted in the paper, in which analytical observation, reproducibility, controlled treatment association and physical mechanism are treated as separate levels of scientific evidence.

11. Conclusions

QREC-MRT is presented in this study as a remote, non-contact and multidomain technology platform whose reported responses can be evaluated through quantitative, falsifiable and progressively controlled experimental methods. The framework developed in this paper separates analytical observation, reproducibility, controlled treatment association and physical mechanism so that these different levels of evidence are not treated as equivalent.

The empirical case study examined coal specimens identified as before-intervention and after-intervention specimens, and analysed independently by SGS India Private Limited. Air-dry GCV increased from 4,057 to 5,160 kcal/kg, corresponding to a between-specimen difference of +27.20%. Dry-basis GCV increased from 4,122 to 5,206 kcal/kg, corresponding to +26.30%. Analysis-sample moisture decreased from 1.57% to 0.88% w/w, corresponding to a relative difference of −43.95%. All three measured differences were in the direction specified by the QREC-MRT coal hypothesis.

The similarity between the air-dry and dry-basis GCV differences is relevant to interpretation. Conversion to a dry basis changed the relative GCV difference by only
0.90 percentage points. The measured difference in analysis-sample moisture alone therefore cannot mathematically account for the observed calorific-value difference between the two specimens.

The present dataset does not, however, establish treatment-specific causation. The study contains one before-labelled and one after-labelled specimen and does not include contemporaneous untreated or sham groups, randomised allocation, blinded treatment assignment or independent experimental replicates. Paired ash, complete proximate and ultimate analyses and complete pre-laboratory chain-of-custody documentation were also unavailable. The measured coal differences are therefore treated as quantitative observational endpoints rather than as a controlled estimate of QREC-MRT efficacy.

This evidentiary distinction does not alter the laboratory values themselves. Instead, it determines the next experimental requirement. A confirmatory coal study should use representative homogenised parent material, prospective allocation to active, sham and untreated groups, blinded analytical coding, independent experimental

replicates, replicate calorimetry, paired compositional measurements and complete chain-of-custody documentation.

Treatment-specific interpretation should be based on prespecified active-control and active-sham contrasts. For a measured endpoint Y, the principal comparisons are:

$$\tau_{TC} = \Delta Y_T - \Delta Y_C$$

and:

$$\tau_{TS} = \Delta Y_T - \Delta Y_S$$

A reproducible response in the active-treatment condition that remains distinguishable from both sham and untreated comparison conditions would move the evidence beyond analytical observation toward controlled treatment association.

The physical coupling mechanism remains a separate experimental question. Photographs, geographic coordinates, sample identifiers and associated metadata are used within QREC-MRT to identify and distinguish the intended target. They are not presented as the physical transmission pathway. Mechanistic investigation should therefore follow reproducible controlled outcomes and employ measurements capable of testing competing conventional and alternative physical explanations.

Coal is used in the present paper as the worked empirical case study, but the quantitative framework is not restricted to coal. QREC-MRT has a broader intended application scope across material, energy and biological systems. Each application domain must, however, define its own primary endpoint, analytical method, relevant comparison conditions, expected variability and criteria for a meaningful treatment-associated response.

The principal contribution of this study is therefore twofold. First, it documents a defined set of independently measured coal observations that provide numerical endpoints for prospective replication. Second, it establishes a general quantitative framework through which QREC-MRT can be tested across application domains without conflating an observed response with treatment causation or physical mechanism.

The resulting framework permits QREC-MRT research to progress in a structured sequence:

measurement ⟶ replication ⟶ controlled treatment association
⟶ mechanistic characterisation

This provides a scientifically testable pathway for evaluating the technology while retaining its broader multidomain research scope.

12. Data Availability

The numerical coal data analysed in this study were derived directly from the SGS India Private Limited analytical reports identified in the manuscript. The measured values, analytical methods, calculated absolute differences and relative differences required to reproduce the quantitative analysis are reported in the paper.

The original laboratory reports and associated supporting documentation may be made available for editorial or scientific verification subject to applicable confidentiality, intellectual-property and third-party document-use requirements.

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14. References

1. Scholes GD. Long-range resonance energy transfer in molecular systems. *Annual Review of Physical Chemistry*. 2003;54:57–87. doi:10.1146/annurev.physchem.54.011002.103746.

2. Förster T. Zwischenmolekulare Energiewanderung und Fluoreszenz. *Annalen der Physik*. 1948;437(1–2):55–75. doi:10.1002/andp.19484370105.

3. Dexter DL. A theory of sensitized luminescence in solids. *Journal of Chemical Physics*. 1953;21(5):836–850. doi:10.1063/1.1699044.

4. Plenio MB, Huelga SF. Dephasing-assisted transport: quantum networks and biomolecules. *New Journal of Physics*. 2008;10:113019. doi:10.1088/1367-2630/10/11/113019.

5. Rebentrost P, Mohseni M, Kassal I, Lloyd S, Aspuru-Guzik A. Environment-assisted quantum transport. *New Journal of Physics*. 2009;11:033003. doi:10.1088/1367-2630/11/3/033003.

6. Ishizaki A, Fleming GR. Theoretical examination of quantum coherence in a photosynthetic system at physiological temperature. *Proceedings of the National Academy of Sciences of the United States of America*. 2009;106(41):17255–17260. doi:10.1073/pnas.0908989106.

7. Engel GS, Calhoun TR, Read EL, Ahn TK, Mančal T, Cheng YC, Blankenship RE, Fleming GR. Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. *Nature*. 2007;446(7137):782–786. doi:10.1038/nature05678.

8. Collini E, Wong CY, Wilk KE, Curmi PMG, Brumer P, Scholes GD. Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature. *Nature*. 2010;463(7281):644–647. doi:10.1038/nature08811.

9. Lambert N, Chen YN, Cheng YC, Li CM, Chen GY, Nori F. Quantum biology. *Nature Physics*. 2013;9:10–18. doi:10.1038/nphys2474.

10. Brookes JC. Quantum effects in biology: golden rule in enzymes, olfaction, photosynthesis and magnetodetection. *Proceedings of the Royal Society A*. 2017;473(2201):20160822. doi:10.1098/rspa.2016.0822.

11. Duan HG, Prokhorenko VI, Cogdell RJ, Ashraf K, Stevens AL, Thorwart M, Miller RJD. Nature does not rely on long-lived electronic quantum coherence for photosynthetic energy transfer. *Proceedings of the National Academy of Sciences of the United States of America*. 2017;114(32):8493–8498. doi:10.1073/pnas.1702261114.

12. McFadden J, Al-Khalili J. The origins of quantum biology. *Proceedings of the Royal Society A*. 2018;474(2220):20180674. doi:10.1098/rspa.2018.0674.

13. Cao J, Cogdell RJ, Coker DF, Duan HG, Hauer J, Kleinekathöfer U, et al. Quantum biology revisited. *Science Advances*. 2020;6(14):eaaz4888. doi:10.1126/sciadv.aaz4888.

14. Ricketti BV, Gauger EM, Fedrizzi A. The coherence time of sunlight in the context of natural and artificial light-harvesting. *Scientific Reports*. 2022;12:5438. doi:10.1038/s41598-022-08693-0.

15. Baikie TK, Wey LT, Lawrence JM, Medipally H, Reisner E, Nowaczyk MM, et al. Photosynthesis re-wired on the pico-second timescale. *Nature*. 2023;615:836–840. doi:10.1038/s41586-023-05763-9.

16. Lawrence JM, Egan RM, Hoefer T, Scarampi A, Shang L, Howe CJ, et al. Rewiring photosynthetic electron transport chains for solar-energy conversion. *Nature Reviews Bioengineering*. 2023;1:887–905. doi:10.1038/s44222-023-00093-x.

17. Couteau C, Barz S, Durt T, Gerrits T, Huwer J, Prevedel R, Rarity J, Shields A, Weihs G. Applications of single photons in quantum metrology, biology and the foundations of quantum physics. *Nature Reviews Physics*. 2023;5:354–363. doi:10.1038/s42254-023-00589-w.

18. Aslam N, Zhou H, Urbach EK, Turner MJ, Walsworth RL, Lukin MD, Park H. Quantum sensors for biomedical applications. *Nature Reviews Physics*. 2023;5:157–169. doi:10.1038/s42254-023-00558-3.

19. International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to electromagnetic fields, 100 kHz to 300 GHz. *Health Physics*. 2020;118(5):483–524. doi:10.1097/HP.0000000000001210.

20. Ramirez-Vazquez R, Escobar I, Vandenbosch GAE, Vargas F, Caceres-Monllor DAC, Arribas E. Measurement studies of personal exposure to radiofrequency electromagnetic fields: a systematic review. *Environmental Research*. 2023;218:114979. doi:10.1016/j.envres.2022.114979.

21. Karipidis K, Brzozek C, Mate R, Bhatt CR, Loughran S, Wood AW. What evidence exists on the impact of anthropogenic radiofrequency electromagnetic fields on animals and plants in the environment? A systematic map. *Environmental Evidence*. 2023;12:9. doi:10.1186/s13750-023-00304-3.

22. Pinto R, Ardoino L, Villani P, Marino C. In vivo studies on radiofrequency electromagnetic-field exposure and cancer: a systematic review. *International Journal of Environmental Research and Public Health*. 2023;20(3):2071. doi:10.3390/ijerph20032071.

23. Ashraf MA, Celik T. Evaluating radiofrequency electromagnetic-field exposure in confined spaces: a systematic review of recent studies and future directions. *Radiation Protection Dosimetry*. 2024;200(6):598–616. doi:10.1093/rpd/ncae045.

24. Meyer F, Bitsch A, Forman HJ, Fragoulis A, Ghezzi P, Henschenmacher B, et al. The effects of radiofrequency electromagnetic-field exposure on biomarkers of oxidative stress in vivo and in vitro: a systematic review of experimental studies. *Environment International*. 2024;194:108940. doi:10.1016/j.envint.2024.108940.

25. Pophof B, Kuhne J, Schmid G, Weiser E, Dorn H, Henschenmacher B, et al. The effect of exposure to radiofrequency electromagnetic fields on cognitive performance in human experimental studies: systematic review and meta-analyses. *Environment International*. 2024;191:108899. doi:10.1016/j.envint.2024.108899.

26. Cordelli E, Ardoino L, Benassi B, Consales C, Eleuteri P, Marino C, et al. Effects of radiofrequency electromagnetic-field exposure on male fertility: a systematic review of experimental studies on non-human mammals and human sperm in vitro. *Environment International*. 2024;185:108509. doi:10.1016/j.envint.2024.108509.

27. Karipidis K, Baaken D, Loney T, Blettner M, Brzozek C, Elwood M, et al. The effect of exposure to radiofrequency fields on cancer risk in the general and working population: a systematic review of human observational studies. Part I: most researched outcomes. *Environment International*. 2024;191:108983. doi:10.1016/j.envint.2024.108983.

28. Bosch-Capblanch X, Esu E, Oringanje CM, Dongus S, Jalilian H, Eyers J, et al. The effects of radiofrequency electromagnetic fields exposure on human self-reported symptoms: a systematic review of human experimental studies. *Environment International*. 2024;187:108612. doi:10.1016/j.envint.2024.108612.

29. Pinto R, Ardoino L, Giardullo P, Villani P, Marino C. A systematic review on the in vivo studies on radiofrequency electromagnetic-field exposure and co-carcinogenesis. *International Journal of Environmental Research and Public Health*. 2024;21(8):1020. doi:10.3390/ijerph21081020.

30. Benke G, Abramson MJ, Brzozek C, McDonald S, Kelsall H, Sanagou M, et al. The effects of radiofrequency exposure on cognition: a systematic review and meta-analysis of human observational studies. *Environment International*. 2024;188:108779. doi:10.1016/j.envint.2024.108779.

31. Hardwicke TE, Wagenmakers EJ. Reducing bias, increasing transparency and calibrating confidence with preregistration. *Nature Human Behaviour*. 2023;7:15–26. doi:10.1038/s41562-022-01497-2.

32. Hohenschurz-Schmidt D, Vase L, Scott W, Annoni M, Ajayi OK, Barth J, et al. Recommendations for the development, implementation, and reporting of control interventions in efficacy and mechanistic trials of physical, psychological, and self-management therapies: the CoPPS Statement. *BMJ*. 2023;381:e072108. doi:10.1136/bmj-2022-072108.

33. Hopewell S, Chan AW, Collins GS, Hróbjartsson A, Moher D, Schulz KF, et al. CONSORT 2025 statement: updated guideline for reporting randomised trials. *BMJ*. 2025;389:e081123. doi:10.1136/bmj-2024-081123.

34. Hopewell S, Chan AW, Collins GS, Hróbjartsson A, Moher D, Schulz KF, et al. CONSORT 2025 explanation and elaboration: updated guideline for reporting randomised trials. *BMJ*. 2025;389:e081124. doi:10.1136/bmj-2024-081124.

35. Wasserstein RL, Lazar NA. The ASA statement on p-values: context, process, and purpose. *The American Statistician*. 2016;70(2):129–133. doi:10.1080/00031305.2016.1154108.

36. Wasserstein RL, Schirm AL, Lazar NA. Moving to a world beyond "p < 0.05." *The American Statistician*. 2019;73(Suppl 1):1–19. doi:10.1080/00031305.2019.1583913.

37. Lakens D. Equivalence tests: a practical primer for *t* tests, correlations, and meta-analyses. *Social Psychological and Personality Science*. 2017;8(4):355–362. doi:10.1177/1948550617697177.

38. Lakens D. Sample size justification. *Collabra: Psychology*. 2022;8(1):33267. doi:10.1525/collabra.33267.

39. International Organization for Standardization. *ISO 5725-1:2023. Accuracy (trueness and precision) of measurement methods and results. Part 1: General principles and definitions*. 2nd ed. Geneva: ISO; 2023.

40. International Organization for Standardization; International Electrotechnical Commission. *ISO/IEC 17025:2017. General requirements for the competence of*

testing and calibration laboratories. 3rd ed. Geneva: ISO; 2017. Corrected version 2018; confirmed 2023.

41. ASTM International. *ASTM D2234/D2234M-20. Standard Practice for Collection of a Gross Sample of Coal*. West Conshohocken, PA: ASTM International; 2020. doi:10.1520/D2234_D2234M-20.

42. ASTM International. *ASTM D2013/D2013M-24. Standard Practice for Preparing Coal Samples for Analysis*. West Conshohocken, PA: ASTM International; 2024.

43. ASTM International. *ASTM D7430/D7430M-22. Standard Practice for Mechanical Sampling of Coal*. West Conshohocken, PA: ASTM International; 2022.

44. ASTM International. *ASTM D6883/D6883M-25. Standard Practice for Manual Sampling of Stationary Coal from Railroad Cars, Barges, Trucks, or Stockpiles*. West Conshohocken, PA: ASTM International; 2025.

45. ASTM International. ASTM D3173/D3173M-17a. Standard Test Method for Moisture in the Analysis Sample of Coal and Coke. West Conshohocken, PA: ASTM International; 2017.

46. ASTM International. *ASTM D3174-12(2018)e1. Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal*. West Conshohocken, PA: ASTM International; 2018.

47. ASTM International. *ASTM D7582-24. Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis*. West Conshohocken, PA: ASTM International; 2024.

48. ASTM International. *ASTM D5865/D5865M-19. Standard Test Method for Gross Calorific Value of Coal and Coke*. West Conshohocken, PA: ASTM International; 2019. doi:10.1520/D5865_D5865M-19.

49. ASTM International. *ASTM D3180-25. Standard Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases*. West Conshohocken, PA: ASTM International; 2025.

50. International Organization for Standardization. *ISO 1928:2025. Coal and coke: Determination of gross calorific value*. 5th ed. Geneva: ISO; 2025.

51. ASTM International. *ASTM D4057-22. Standard Practice for Manual Sampling of Petroleum and Petroleum Products*. West Conshohocken, PA: ASTM International; 2022.

52. ASTM International. *ASTM D4052-22. Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter*. West Conshohocken, PA: ASTM International; 2022. doi:10.1520/D4052-22.

53. ASTM International. *ASTM D445. Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids and Calculation of Dynamic Viscosity*. West Conshohocken, PA: ASTM International.

54. ASTM International. *ASTM D93. Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester*. West Conshohocken, PA: ASTM International.

55. ASTM International. *ASTM D240-25. Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter*. West Conshohocken, PA: ASTM International; 2025. doi:10.1520/D0240-25.

56. ASTM International. *ASTM D4809-25. Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter, Precision Method*. West Conshohocken, PA: ASTM International; 2025.

57. International Organization for Standardization. *ISO 10715:2022. Natural gas: Gas sampling*. 2nd ed. Geneva: ISO; 2022.

58. International Organization for Standardization. *ISO 6974-1:2012. Natural gas: Determination of composition and associated uncertainty by gas chromatography. Part 1: General guidelines and calculation of composition*. Geneva: ISO; 2012.

59. International Organization for Standardization. *ISO 6976:2016. Natural gas: Calculation of calorific values, density, relative density and Wobbe indices from composition*. 3rd ed. Geneva: ISO; 2016. Confirmed 2022.

60. Boehm RC, Yang Z, Bell DC, Faulhaber C, Mayhew EK, Bauder U, Eckel G, Heyne JS. Perspective on fuel-property blending rules for design and qualification of aviation fuels: a review. *Energy & Fuels*. 2024;38(18):17128–17145. doi:10.1021/acs.energyfuels.4c02457.

61. International Electrotechnical Commission. *IEC 61724-1:2021. Photovoltaic system performance. Part 1: Monitoring*. 2nd ed. Geneva: IEC; 2021.

62. International Electrotechnical Commission. *IEC TS 61724-2:2025. Photovoltaic system performance. Part 2: Power performance index and capacity evaluation method*. 2nd ed. Geneva: IEC; 2025.

63. International Electrotechnical Commission. *IEC TS 61724-3:2016. Photovoltaic system performance. Part 3: Energy evaluation method*. Geneva: IEC; 2016. Incorporating Corrigendum 1:2018.

64. Marion B, Adelstein J, Boyle K, Hayden H, Hammond B, Fletcher T, et al. Performance parameters for grid-connected PV systems. In: *Proceedings of the 31st IEEE Photovoltaic Specialists Conference*. Lake Buena Vista, FL: IEEE; 2005. p. 1601–1606. doi:10.1109/PVSC.2005.1488451.

65. Faiman D. Assessing the outdoor operating temperature of photovoltaic modules. *Progress in Photovoltaics: Research and Applications*. 2008;16(4):307–315. doi:10.1002/pip.813.

66. Micheli L, Muller M. An investigation of the key parameters for predicting PV soiling losses. *Progress in Photovoltaics: Research and Applications*. 2017;25(4):291–307. doi:10.1002/pip.2860.

67. Maxwell K, Johnson GN. Chlorophyll fluorescence: a practical guide. *Journal of Experimental Botany*. 2000;51(345):659–668. doi:10.1093/jexbot/51.345.659.

68. Baker NR. Chlorophyll fluorescence: a probe of photosynthesis in vivo. *Annual Review of Plant Biology*. 2008;59:89–113. doi:10.1146/annurev.arplant.59.032607.092759.

69. Kramer DM, Johnson G, Kiirats O, Edwards GE. New fluorescence parameters for the determination of QA redox state and excitation-energy fluxes. *Photosynthesis Research*. 2004;79(2):209–218. doi:10.1023/B:PRES.0000015391.99477.0d.

70. Poorter H, Fiorani F, Stitt M, Schurr U, Finck A, Gibon Y, et al. The art of growing plants for experimental purposes: a practical guide for the plant biologist. *Functional Plant Biology*. 2012;39(11):821–838. doi:10.1071/FP12028.

71. Papoutsoglou EA, Athanasiadis IN, Visser RGF, Finkers R. The benefits and struggles of FAIR data: the case of reusing plant phenotyping data. *Scientific Data*. 2023;10:457. doi:10.1038/s41597-023-02364-z.

72. Wang T, Sun S, Yin Y, Zhao J, Tang Y, Wang Y, Gao F, Luan X. Status of crop water-use-efficiency evaluation methods: a review. *Agricultural and Forest Meteorology*. 2024;349:109961. doi:10.1016/j.agrformet.2024.109961.

73. Antu UB, Islam MS, Ahmed S, Arifuzzaman M, Saha S, Mitu PR, et al. Emerging technologies for efficient water use in agriculture: a review of current trends and future directions. *Journal of Water Process Engineering*. 2024;68:106317. doi:10.1016/j.jwpe.2024.106317.

74. Steeneken PG, Kaiser E, Verbiest GJ, ten Veldhuis MC. Sensors in agriculture: towards an Internet of Plants. *Nature Reviews Methods Primers*. 2023;3:60. doi:10.1038/s43586-023-00250-x.

75. Mittler R, Zandalinas SI, Fichman Y, Van Breusegem F. Reactive oxygen species signalling in plant stress responses. *Nature Reviews Molecular Cell Biology*. 2022;23:663–679. doi:10.1038/s41580-022-00499-2.

76. Trivedi P, Leach JE, Tringe SG, Sa T, Singh BK. Plant–microbiome interactions: from community assembly to plant health. *Nature Reviews Microbiology*. 2020;18:607–621. doi:10.1038/s41579-020-0412-1.

77. Banerjee S, van der Heijden MGA. Soil microbiomes and one health. *Nature Reviews Microbiology*. 2023;21:6–20. doi:10.1038/s41579-022-00779-w.

78. Compant S, Cassan F, Kostić T, Johnson L, Brader G, Trognitz F, Sessitsch A. Harnessing the plant microbiome for sustainable crop production. *Nature Reviews Microbiology*. 2025;23:9–23. doi:10.1038/s41579-024-01079-1.

79. Mooney SJ, Castrillo G, Cooper HV, Bennett MJ. Root–soil–microbiome management is key to the success of regenerative agriculture. *Nature Food*. 2024;5:451–453. doi:10.1038/s43016-024-01001-1.

80. De Micco V, Arena C, Pignalosa D, Durante M. Effects of sparsely and densely ionizing radiation on plants. *Radiation and Environmental Biophysics*. 2011;50(1):1–19. doi:10.1007/s00411-010-0343-8.

81. Caplin N, Willey N. Ionizing radiation, higher plants, and radioprotection: from acute high doses to chronic low doses. *Frontiers in Plant Science*. 2018;9:847. doi:10.3389/fpls.2018.00847.

82. De Micco V, Arena C, Di Fino L, Narici L. Radiation environment in exploration-class space missions and plants' responses relevant for cultivation in bioregenerative life-support systems. *Frontiers in Plant Science*. 2022;13:1001158. doi:10.3389/fpls.2022.1001158.

83. Pagliarello R, Bennici E, Di Sarcina I, Villani ME, Desiderio A, Nardi L, Benvenuto E, Cemmi A, Massa S. Effects of gamma radiation on engineered tomato biofortified for space agriculture by morphometry and fluorescence-based indices. *Frontiers in Plant Science*. 2023;14:1266199. doi:10.3389/fpls.2023.1266199.

84. Maffei ME, Balestrini R, Costantino P, Lanfranco L, Morgante M, Battistelli A, et al. The physiology of plants in the context of space exploration. *Communications Biology*. 2024;7:1311. doi:10.1038/s42003-024-06989-7.

85. Yates K, Berliner AJ, Makrygiorgos G, Kaiyom F, McNulty MJ, Khan I, et al. Nitrogen accountancy in space agriculture. *npj Microgravity*. 2024;10:90. doi:10.1038/s41526-024-00428-x.

86. Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*. 2016;3:160018. doi:10.1038/sdata.2016.18.

87. Jones D, Snider C, Nassehi A, Yon J, Hicks B. Characterising the digital twin: a systematic literature review. *CIRP Journal of Manufacturing Science and Technology*. 2020;29:36–52. doi:10.1016/j.cirpj.2020.02.002.

88. Li X, Feng M, Ran Y, Su Y, Liu F, Huang C, et al. Big Data in Earth system science and progress towards a digital twin. *Nature Reviews Earth & Environment*. 2023;4:319–332. doi:10.1038/s43017-023-00409-w.

89. Kim S, Heo S. An agricultural digital twin for mandarins demonstrates the potential for individualized agriculture. *Nature Communications*. 2024;15:1561. doi:10.1038/s41467-024-45725-x.

90. International Organization for Standardization. *ISO 19115-1:2014. Geographic information: Metadata. Part 1: Fundamentals*. Geneva: ISO; 2014. Including Amendments 1:2018 and 2:2020.