Development of a Climate-Responsive Conceptual Model for Controlled Nutrient Release from Nanofertilizers Under Agricultural Stress Conditions

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Abstract

Nanofertilizers are increasingly promoted as a route to higher nutrient use efficiency (NUE), yet most formulations are engineered and tested to release nutrients at rates that are fixed by material chemistry rather than by the field conditions that climate change is making more variable. Drought, heat waves, salinization and waterlogging alter soil water flux, temperature-dependent diffusion, ion exchange and microbial transformation at the same moment they alter crop nutrient demand, so a carrier that releases on a fixed schedule is likely to deliver nutrients when plants cannot use them and to withhold them when recovery growth begins. This paper develops the Climate-Responsive Controlled Release (CRCR) conceptual model, which links six layers: (1) a multivariate climate stress state, (2) stimuli-responsive nanocarrier gates, (3) stress-modulated release kinetics, (4) stress-adjusted plant demand and uptake, (5) environmental fate of released nutrients and of the nanomaterial itself, and (6) sensing, forecasting and management feedback. The model formalizes release as a first-order or Korsmeyer-Peppas process whose rate constant is the product of a reference constant and dimensionless response functions for temperature, soil moisture, pH and electrical conductivity, and it introduces a Synchrony Index (SI) that quantifies the temporal match between nutrient release and stress-adjusted demand. Stress-specific design logic is derived for drought, heat, salinity, waterlogging and compound events, and ten testable propositions are stated. An illustrative simulation with hypothetical parameters shows how a moisture-gated, heat-compensated carrier can raise SI from 0.15 to 0.85 relative to a conventional temperature-sensitive carrier delivering the same nutrient dose, while also exposing a rewetting-pulse risk that the model treats as a design constraint. A staged validation roadmap, implications for smallholder systems in climate-exposed regions, and the model's limitations are discussed. The CRCR model is intended as a shared framework for material scientists, agronomists and policy makers to design, test and regulate nanofertilizers against climate stress rather than average conditions.

Keywords: Nanofertilizer; controlled release; climate resilience; abiotic stress; stimuli-responsive materials; nutrient use efficiency; synchrony; conceptual model.

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1. Introduction

1.1 Background and problem statement

Global agriculture must raise output while operating under a climate that is warmer, more variable and more prone to extremes. The Intergovernmental Panel on Climate Change reports that human-induced warming has already increased the frequency and intensity of hot extremes, agricultural and ecological droughts, and heavy precipitation in many regions (IPCC, 2023). Extreme weather events have measurably reduced national cereal production, with drought and extreme heat causing average losses on the order of 9 to 10 percent in affected years (Lesk et al., 2016), and each degree of warming is expected to depress yields of the major cereals (Zhao et al., 2017). These yield effects are partly mediated by nutrition: stress changes how much nutrient a crop needs, how much it can take up, and how much is lost from the soil before uptake occurs.

For agrarian economies the stakes are especially high, because household food security and income stability depend directly on whether climate-smart practices can be adopted at scale (Michael & Ogunsola, 2021d), and because predictive data models for crop resilience and climate adaptation are only beginning to inform farm decisions (Michael & Ogunsola, 2023c). Access to reliable energy for irrigation further shapes how far smallholders can buffer water stress (Michael & Ogunsola, 2024a), and the alignment of national policy with global climate diplomacy goals and regional sustainable development commitments sets the wider frame for adaptation investment (Liadi, 2022, 2023).

Nutrient management already performs poorly under average conditions. Global cropland nitrogen use efficiency has hovered around 40 to 50 percent for decades, meaning that roughly half of applied nitrogen is lost to the environment as nitrate, ammonia or nitrous oxide (Lassaletta et al., 2014; Zhang et al., 2015). Losses are not evenly distributed in time: they concentrate in windows when nutrient supply exceeds crop uptake, such as heavy rain after fertilization, rewetting of dry soils, or periods when stressed crops stop growing. Climate change widens and multiplies these mismatch windows.

In West African and wider Sub-Saharan settings, these losses interact with pronounced spatial variability in soil properties, as geostatistical assessments of agricultural soils in southwest Nigeria illustrate (Kianguebene-Koussingounina et al., 2023). They also interact with institutional constraints. Agricultural policy frameworks are not always aligned with national sustainable development priorities (Michael & Ogunsola, 2021a), although data-driven policy models and quantitative agricultural economics can improve production efficiency and resource optimization (Michael & Ogunsola, 2021c, 2023a). Digital agriculture tools and platform integration are reshaping decision-making and market access (Michael & Ogunsola, 2021b, 2023b), yet extension services, socioeconomic barriers, gender inequities and limited access to agribusiness finance continue to slow the adoption of new inputs (Michael & Ogunsola, 2021e, 2022a, 2022b, 2019a). Agribusiness education, entrepreneurship and rural innovation hubs (Michael & Ogunsola, 2019b, 2023e, 2023d), international research collaboration (Michael & Ogunsola, 2024c) and circular economy approaches (Michael & Ogunsola, 2024b) are therefore part of the enabling environment into which any nanofertilizer innovation must fit. Value-chain linkages to household economic

stability, export promotion under the African Continental Free Trade Area, market access under trade agreements, harmonized digital trade rules, and AI-supported customs facilitation further condition whether improved inputs reach farmers at an affordable price (Jones & Ominyi, 2021, 2022b, 2022a, 2024a, 2024b).

Controlled-release and slow-release fertilizers were developed to reduce such losses by extending nutrient supply over time (Shaviv, 2001; Trenkel, 2010; Azeem et al., 2014). Nanofertilizers extend this logic by encapsulating, adsorbing or intercalating nutrients in nanoscale carriers such as hydroxyapatite, layered double hydroxides (LDH), mesoporous silica, chitosan, clay nanocomposites and polymer hydrogels, or by supplying nutrients as nanoparticles with high reactive surface area (Raliya et al., 2018; Dimkpa & Bindraban, 2018; Guo et al., 2018). Urea-hydroxyapatite nanohybrids, for example, have been shown to release nitrogen more slowly than conventional urea and to sustain yield at reduced application rates (Kottegoda et al., 2017). Critical evaluations nonetheless caution that reported gains are variable and that many studies compare nano formulations against weak baselines under controlled, non-stressed conditions (Kah et al., 2018; Kah et al., 2019).

A central limitation is that most controlled-release designs, nano or conventional, are optimized for a release profile that is either fixed or driven by environmental variables in ways that work against crop needs. Polymer-coated urea typically releases faster at higher temperature (Shaviv, 2001), which is precisely when a heat-stressed crop may slow its growth. Diffusion-driven systems release little when soils are dry and then pulse when soils rewet, coinciding with high leaching and denitrification risk. Anion-exchange carriers such as LDH can release nitrate or phosphate faster in saline soils as chloride competes for exchange sites. In each case the carrier responds to climate, but not in a way that is aligned with plant demand.

1.2 Climate stress and soil-plant nutrient dynamics

Abiotic stresses alter nutrient availability through both soil and plant pathways. In the soil, water content controls the diffusion and mass flow that carry nutrients to roots; as soils dry, effective diffusion coefficients fall sharply and mass flow nearly stops, so even nutrients that are present become positionally unavailable. Rewetting of dry soil triggers a burst of microbial mineralization and respiration, and in nitrogen systems this can drive short, intense pulses of nitrous oxide emission and nitrate leaching (Butterbach-Bahl et al., 2013). Temperature raises the rates of hydrolysis, mineralization, nitrification and volatilization, typically with Q_{10} values between about 2 and 3. Salinity increases ionic strength and competing ions, alters sorption equilibria, and impairs root uptake through osmotic and ion-specific effects. Waterlogging creates hypoxic conditions that suppress root respiration and uptake while accelerating denitrification.

In the plant, stress reduces growth and therefore the sink strength that drives nutrient demand, and it can damage root uptake systems directly. Field crops frequently experience several stresses simultaneously or in sequence, and the physiological response to combined stress is not simply the sum of single-stress responses (Mittler, 2006). The practical consequence is that the nutrient requirement of a crop in a stressed season has a different shape over time, not merely a lower total, than the requirement assumed by fertilizer recommendations built on average years.

Approaches developed in adjacent fields show how climate exposure can be parameterized for decision-making. Hydrological models have been used to assess climate-induced watershed vulnerability (Badmus & Olamide, 2019), and integrated conceptual models of heat stress risk have been developed for industrial operations in extreme environments (Arumosoye & Obriki, 2018). Frameworks that integrate climate data with health outcomes (Oparah et al., 2024b) and architectural interventions to reduce flood vulnerability in African cities (Nwafor et al., 2019a) treat climate as a time-varying, location-specific driver rather than an average. Building-envelope studies in humid regions translate climatic variables directly into design parameters (Nwafor et al., 2018), statistical models estimate daily solar radiation from routine weather data (Odejobi & Ahmed, 2018), and studies of battery storage in hot, weak-grid regions show how heat accelerates material degradation and shifts optimal control (Komi & Ganiu, 2022). Livestock research offers a biological parallel: physiological stress indices of scavenging chickens respond to environmental exposure near industrial sites (Oluwadele et al., 2023). These studies reinforce the CRCR premise that stress modifies both supply and demand.

1.3 Nanofertilizers and release mechanisms

Nanofertilizers can be grouped into three classes: nanoscale nutrient particles (for example zinc oxide or iron oxide nanoparticles), nanomaterial-enhanced conventional fertilizers (for example nano-coated urea), and nanocarriers that host conventional nutrients (Dimkpa & Bindraban, 2018; Zulfiqar et al., 2019). Release from carriers occurs through some combination of Fickian diffusion through a matrix or coating, polymer swelling and relaxation, surface or bulk erosion and dissolution, ion exchange, and biologically mediated degradation by enzymes or root exudates (Siepmann & Siepmann, 2012; Guo et al., 2018). Each of these mechanisms has a characteristic sensitivity to environmental variables. Diffusion scales with temperature and with the water-filled pore network; swelling responds to water activity, pH and ionic strength; dissolution of calcium phosphate phases such as hydroxyapatite accelerates as pH falls; and ion exchange depends on the concentration and charge of competing ions.

Release curves are commonly fitted with empirical or semi-mechanistic equations such as zero-order, first-order, Higuchi and Korsmeyer-Peppas models (Korsmeyer et al., 1983; Peppas & Sahlin, 1989). These fits are almost always obtained in water or buffer at a single temperature, which means the fitted parameters describe the carrier under one reference condition and say little about its behaviour across the stress gradient it will meet in the field.

Materials science outside agriculture provides useful analogues for how nanoscale and thin-film materials behave under environmental stress. Theoretical analysis of charge transport and recombination losses in thin-film architectures shows that nanostructure performance depends strongly on interfaces and operating conditions (Atta et al., 2024), and reliability engineering and failure analysis in complex systems (Gideon et al., 2019) and lifecycle reliability assessment (Makut et al., 2024) offer methods for anticipating how carrier coatings might degrade in hot, wet or saline soils. Corrosion science adds two further lessons: green corrosion inhibitors can be derived from agricultural extracts for acidic and alkaline media (Atta et al., 2018), and corrosion risk and material selection must be matched to aggressive service environments (Atta et al., 2020; Obetta et al., 2020), which is analogous to matching carrier chemistry to soil pH and salinity. Sustainable

materials selection in laboratory facilities (Ogbete et al., 2020) illustrates the same principle of choosing materials for durability in demanding conditions.

Nanomaterials are already used to control delivery and biological activity in related domains. Nanomaterials have been proposed for improved drug delivery within healthcare supply chains (Ike et al., 2024), and artificial intelligence combined with advanced biosensors enables rapid detection of antimicrobial-resistant foodborne pathogens (Olorunkosebi et al., 2023). Evidence that environmental microplastics can act as vectors for avian virus transmission within a One Health framework (Ayinde et al., 2024) underlines why persistent particulate residues in agricultural soils warrant scrutiny.

1.4 Stimuli-responsive delivery as a design paradigm

Biomedical drug delivery has long used stimuli-responsive carriers that change release in response to temperature, pH, ionic strength, redox state or enzymes. Agricultural adaptations are emerging, including pH-responsive and enzyme-degradable coatings, moisture-swelling superabsorbent hydrogels, and thermo-responsive polymers whose solubility changes around a lower critical solution temperature (Lowry et al., 2019; Kah et al., 2019). Reviews of nano-enabled agriculture have argued that the most valuable property of nanomaterials may be their ability to target delivery and respond to plant or environmental cues rather than simply to slow release (Lowry et al., 2019; Gilbertson et al., 2020). However, these discussions have rarely been organized around climate stress as the design driver, and they lack a common metric for judging whether a responsive carrier actually serves the crop better.

1.5 Climate resilience as an evaluation lens

Resilience, in the ecological sense, refers to the capacity of a system to absorb disturbance and retain its essential function (Holling, 1973). Applied to crop nutrition, a resilient nutrient supply system is one that keeps nutrient availability matched to crop need through a disturbance and supports rapid recovery afterward, while limiting losses. This lens shifts the evaluation of fertilizers from mean NUE under favourable conditions toward the stability of NUE and yield across stressful conditions, and toward the avoidance of loss pulses during transitions such as drought-to-rewetting.

The resilience concept has been operationalized in several applied fields that the CRCR model draws on. Supply chain studies have proposed resilience indices and predictive models for vendor risk (Efobi et al., 2023; Anene, 2021), resilience frameworks for critical infrastructure and national energy reliability (Ogunwole et al., 2021; Okonkwo et al., 2024b), contractual resilience in energy supply chains (Uchechi et al., 2020), and resilient logistics and localized supply solutions that integrate predictive analytics and IoT to strengthen community resilience (Anene & Clement, 2022, 2024). Pharmaceutical supply chains offer parallel strategies for mitigating disruption and sustaining availability of essential products (Awulu et al., 2022; Akinleye, 2024). Their shared emphasis on absorbing shocks, maintaining function and recovering quickly maps directly onto the nutrient-supply problem.

1.6 Organic residues, feed systems and nutrient cycling

Nanocarriers derived from biochar, cellulose, chitosan or other bio-based matrices connect nanofertilizer design to the wider flow of agricultural residues. Livestock nutrition research in West Africa has characterized many of these residue streams. Studies have evaluated Pennisetum purpureum silage supplemented with farm residues and its effect on growth and meat quality (Oluwadele et al., 2024b), the meat quality of rams fed Napier grass silage, ensiled sorghum and crop residues (Oluwadele et al., 2024a), and mango leaves and other alternative feeds for rams (Oluwadele et al., 2024c). Other work has examined Gmelina arborea leaves with cassava peel concentrates (Aye & Tawose, 2015, 2016) and water hyacinth and cassava peel silage (Tawose et al., 2023b, 2024). Characterization of indigenous chicken phenotypes (Ekeocha et al., 2021) and aflatoxin contamination in poultry feeds (Tawose et al., 2023a) underline the importance of quality control across these residue-based systems. Simple processing machinery, including poultry de-feathering machines and a gum production machine using cassava waste peels (Bello et al., 2022a, 2022b, 2024), shows that local residues can be converted into value-added materials, a pathway that could also supply low-cost carrier matrices. Integrating nutrient release from nanofertilizers with manure and residue cycling is therefore a natural extension of the model.

1.7 Research gaps and objectives

The literature reviewed above reveals five gaps that motivate the present model:

- **Fixed-condition characterization.** Release kinetics are reported at a single temperature and moisture state, so stress sensitivity is unknown for most formulations.
- **Misaligned responsiveness.** Where carriers do respond to environment (for example temperature-accelerated diffusion), the direction of response is often opposite to crop need.
- **No demand coupling.** Release is evaluated against time, not against the crop's stress-adjusted demand curve, so synchrony is not measured.
- **Incomplete fate accounting.** Few studies close the mass balance for released nutrients or track the transformation and persistence of the carrier under stress (Hofmann et al., 2020).
- **Weak field validation.** Evidence comes largely from greenhouse or laboratory studies under non-stressed conditions (Kah et al., 2018).

This paper addresses these gaps by asking: **how should the nutrient release behaviour of nanofertilizers be conceptualized so that it is explicitly responsive to agricultural climate stress, and how can that responsiveness be designed, measured and tested?** The objectives are to (i) synthesize what is known about the interaction of climate stressors with nanocarrier release mechanisms and crop nutrient demand; (ii) build a layered conceptual model, the Climate-Responsive Controlled Release (CRCR) model, that formalizes these interactions; (iii) derive stress-specific design principles and testable propositions; and (iv) outline a validation and implementation roadmap. The contribution is conceptual: the model is a structured, partially quantified framework intended to organize empirical work, not a calibrated predictive tool.

The remainder of the paper is organized as follows. Section 2 describes the research method used to develop the model. Section 3 presents and discusses the results: the CRCR conceptual model

and its formal relationships, testable propositions, an illustrative simulation, stress-specific design logic, the model's position relative to existing work, implications, limitations and future research. Section 4 concludes.

2. Research Method

2.1 Research design

This study adopts a conceptual model development design. Rather than collecting new primary data, it integrates evidence from multiple disciplines into a structured, partially quantified framework whose relationships can later be tested empirically. This design is appropriate where a phenomenon spans several fields that have not yet been connected, as is the case for nanocarrier chemistry, soil nutrient dynamics, crop stress physiology and climate risk.

2.2 Model development procedure

The CRCR model was developed through a theory-building procedure adapted from Jabareen's (2009) method for constructing conceptual frameworks, combined with the conventions of semi-quantitative process modelling. The procedure had six steps:

- **Mapping data sources.** Literature on nanofertilizer chemistry, controlled-release kinetics, soil nutrient transformations under abiotic stress, crop stress physiology and nanomaterial environmental fate was identified across materials science, soil science, agronomy and environmental science.
- **Extracting and categorizing concepts.** Recurring constructs (stress variables, release mechanisms, demand, uptake, loss pathways, management levers) were extracted and grouped by function.
- **Identifying causal linkages.** Directional relationships between constructs were identified, for example the dependence of diffusion-controlled release on temperature and water-filled porosity.
- **Integrating into layers.** Concepts were integrated into six functional layers ordered along the causal chain from climate driver to outcome, with explicit feedback loops.
- **Formalization.** Where the underlying science supports it, relationships were expressed as equations drawn from established kinetic and transport theory, using dimensionless response functions to keep the model material-agnostic.
- **Synthesis and proposition building.** The integrated model was used to derive stress-specific design logic and testable propositions, and an illustrative simulation was used to check internal consistency.

2.3 Scope and boundary conditions

The model is scoped to soil-applied nanocarriers delivering macronutrients (nitrogen, phosphorus, potassium) and micronutrients in annual cropping systems, though the logic extends to foliar delivery (Hong et al., 2021). It treats the field as a homogeneous root zone at the timescale of days, which is appropriate for a conceptual framework but is relaxed in the validation roadmap.

3. Results and Discussion

The principal result of this study is the Climate-Responsive Controlled Release (CRCR) conceptual model. This section first presents the model's architecture and formal relationships, its testable propositions and an illustrative simulation, and then discusses the model under specific stress scenarios, its position relative to existing frameworks, its implications, limitations and directions for future research.

3.1 Architecture of the CRCR model

The CRCR model consists of six interacting layers (Figure 1). Climate stress inputs (Layer 1) act on a responsive nanocarrier (Layer 2), whose gates modulate release kinetics (Layer 3). Released nutrients enter the root-zone pool, where they are either taken up according to stress-adjusted plant demand (Layer 4) or partitioned to loss pathways and transformations (Layer 5). Sensing, forecasting and management (Layer 6) close the loop by informing application timing, formulation choice and future carrier redesign. Outcomes are expressed as NUE, yield stability, losses and a composite resilience index.

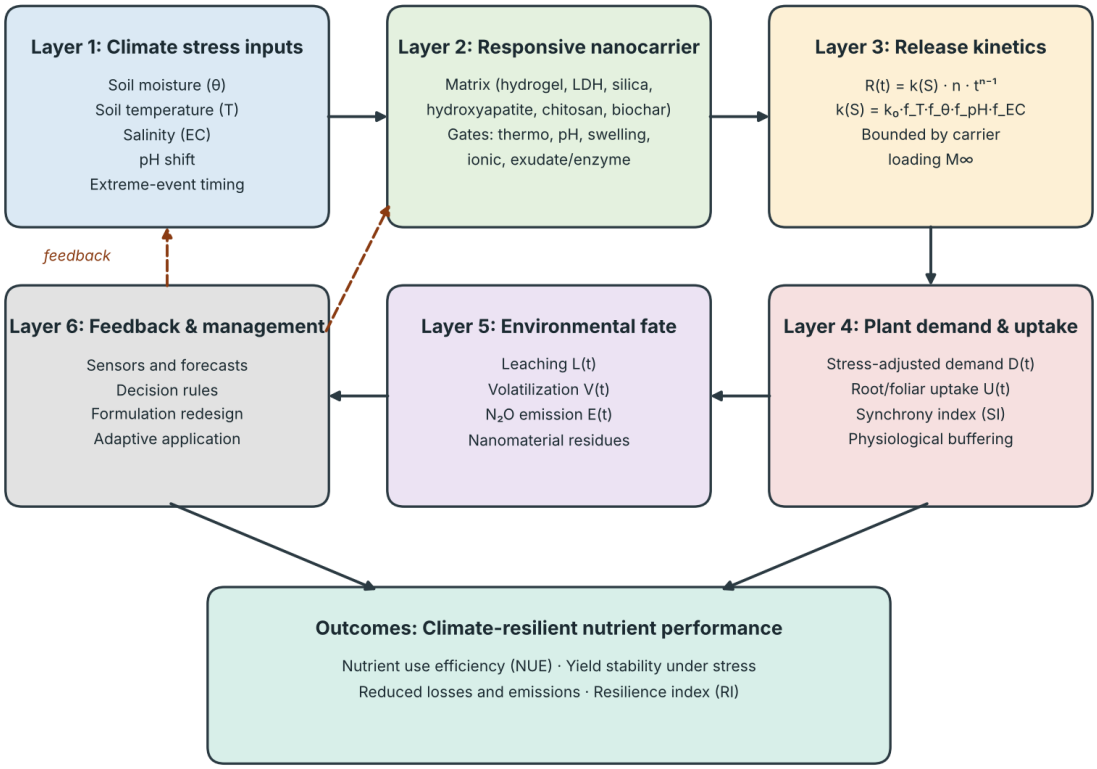


Figure 1. The six-layer Climate-Responsive Controlled Release (CRCR) conceptual model. Solid arrows show the primary causal chain; dashed arrows show feedback from sensing and management to stress anticipation and carrier design.

3.2 Layer 1: Climate stress state

The stress environment is represented as a time-varying state vector of root-zone conditions:

$$S(t) = [\ \theta(t), T(t), EC(t), pH(t), O_2(t)\ ] \quad (1)$$

where θ is volumetric soil water content, T is soil temperature, EC is electrical conductivity of the soil solution (a proxy for salinity), pH is soil solution pH and O_2 is soil oxygen status (a proxy for waterlogging). The model treats S(t) at the root-zone scale and recognizes that stress is defined by both magnitude and timing: a dry spell during vegetative growth and one during grain filling are different events because demand differs. Stress events can be characterized by onset, duration, intensity and the rate of transition back to non-stressed conditions, since transitions (rewetting, cooling, flushing of salts) are often when losses peak.

3.3 Layer 2: Responsive nanocarrier and gating functions

The carrier is described by its nutrient loading M_0, its dominant release mechanism, and a set of gates, each of which translates one element of S(t) into a dimensionless multiplier on release rate. A gate value of 1 means release proceeds at the reference rate; values below 1 throttle release and values above 1 accelerate it. The combined gating function is:

$$\Phi(S) = f_T(T) \cdot f_\theta(\theta) \cdot f_{pH}(pH) \cdot f_{EC}(EC) \cdot f_B(t) \quad (2)$$

The multiplicative form assumes that the gates act independently, an assumption that is reasonable as a first approximation and is examined as Proposition P5 in Section 3.9. Representative forms for each gate are:

$$f_T(T) = Q_{10}^{(T - Tref)/10} \cdot g_T(T) \quad (3)$$

$$f_\theta(\theta) = 1 / [\ 1 + \exp(\ -\beta_\theta\ (\theta - \theta_c)\ )\ ] \quad (4)$$

$$f_{EC}(EC) = 1 + \alpha_{EC}\ (EC - EC_{ref}) \quad (5)$$

In Equation 3 the Q_{10} term captures the intrinsic temperature sensitivity of diffusion and dissolution, and $g_T(T)$ is an optional compensating term contributed by a thermo-responsive component, such as a polymer that contracts and densifies above a threshold temperature, which can offset or reverse the Q_{10} acceleration. Equation 4 is a sigmoidal moisture gate with threshold θ_c and steepness β_θ, representing hydrogel swelling or water-bridge formation that permits release only when soil moisture is sufficient for transport to roots. Equation 5 is a linearized ionic sensitivity term in which α_{EC} is positive for ion-exchange carriers (salinity accelerates release) and can be engineered toward zero by ionic shielding or selective exchange chemistry. The pH gate f_{pH} can take sigmoidal form around the dissolution threshold of the carrier phase. The biological gate $f_B(t)$ represents release triggered by root exudates or rhizosphere enzymes and therefore links release to the presence and activity of roots, which is the most direct proxy for demand.

Table 1 summarizes how each stressor affects the dominant release mechanisms, what the desired carrier response is from the crop's perspective, and candidate material strategies.

Table 1. Stressor-mechanism-response matrix for climate-responsive nanocarriers

Stressor	Typical effect on conventional release	Desired carrier response	Candidate material strategies
Drought (low θ)	Diffusion slows; nutrients accumulate near granule; pulse on rewetting	Hold nutrients during drought; meter (not dump) release on rewetting	Moisture-gated hydrogels; nanoclay-polymer composites with tortuous paths; biochar-hosted carriers
Heat (high T)	Q_{10} acceleration of diffusion and hydrolysis; volatilization risk	Flat or reduced release above crop heat threshold	Thermo-responsive polymer shells; dense inorganic coatings with low activation energy
Salinity (high EC)	Competitive ion exchange accelerates anion release (e.g., LDH); osmotic limits on uptake	Release insensitive to ionic strength; co-delivery of K and Ca to support ion balance	Selective-exchange LDH; silica shells; chitosan-based carriers with ionic shielding
Waterlogging (low O_2)	Saturation accelerates leaching and denitrification of released N	Suppress N release under saturation; avoid nitrate accumulation	Hydrophobic or redox-sensitive coatings; co-formulated nitrification inhibitors
Acidification or alkalinization (pH shift)	Dissolution of phosphate phases accelerates at low pH; precipitation at high pH	Release tuned to rhizosphere pH, not bulk soil	pH-buffered hydroxyapatite; exudate-responsive coatings
Compound events	Non-additive interactions; transitions drive loss pulses	Prioritize transition control and demand coupling	Multi-gate architectures; biological (root-triggered) gates

3.4 Layer 3: Stress-modulated release kinetics

Release is modelled with a reference kinetic law whose rate constant is modulated by the gating function. For carriers whose release approximates first-order behaviour:

$$dM_r/dt = k_0 \cdot \Phi(S(t)) \cdot (M_0 - M_r) \quad (6)$$

where M_r is cumulative nutrient released and k_0 is the reference rate constant measured at reference conditions S_{ref}. For swelling-controlled or anomalous transport, the Korsmeyer-Peppas form (Korsmeyer et al., 1983) is generalized by replacing clock time with a stress-weighted effective time τ:

$$M_r/M_0 = k_0 \cdot \tau^n, \quad \text{where } \tau(t) = \int_0^t \Phi(S(s))\, ds \quad (7)$$

The exponent n retains its usual mechanistic interpretation (values near 0.5 for Fickian diffusion in thin films, approaching 1 for relaxation-controlled transport). The effective-time formulation is useful because it collapses a variable climate history into a single quantity that can be measured: two carriers exposed to the same weather will have different τ trajectories if their gates differ. An initial burst fraction can be added where surface-adsorbed nutrient is released on first wetting.

3.5 Layer 4: Stress-adjusted demand, uptake and synchrony

Crop demand is represented as a potential demand curve $D_p(t)$, determined by crop, cultivar and growth stage, scaled by a stress modifier $\psi(S)$ between 0 and 1:

$$D(t) = D_p(t) \cdot \psi(S(t)) \tag{8}$$

Actual uptake U(t) is limited by the smaller of demand and the root's capacity to acquire nutrient from the solution, which can be represented with Michaelis-Menten kinetics scaled by a moisture-dependent transport factor:

$$U(t) = \min\{ D(t), U_{max} \cdot C(t) / (K_m + C(t)) \cdot h(\theta) \} \tag{9}$$

where C(t) is root-zone solution concentration and $h(\theta)$ reflects the decline of diffusion and mass flow in dry soil. The central performance concept of the CRCR model is the **Synchrony Index (SI)**, which measures how closely the release flux follows stress-adjusted demand over the season:

$$SI = 1 - \int |R(t) - D(t)| \, dt / \int [R(t) + D(t)] \, dt \tag{10}$$

where $R(t) = dM_r/dt$ is the release flux. SI ranges from 0 (no temporal overlap) to 1 (perfect match). When cumulative release equals cumulative demand, SI isolates the timing problem from the dose problem. Because losses occur mostly when release exceeds uptake, SI is expected to be a strong predictor of NUE under stress, which is stated formally as Proposition 1.

3.6 Layer 5: Environmental fate and mass balance

Released nutrient enters a root-zone pool N_s whose dynamics follow a mass balance:

$$dN_s/dt = R(t) - U(t) - L(t) - V(t) - E(t) - I(t) \tag{11}$$

where L is leaching (proportional to drainage flux and concentration), V is volatilization (primarily ammonia, increasing with temperature and pH), E is gaseous loss through nitrification and denitrification including nitrous oxide (increasing with water-filled pore space, temperature and nitrate availability), and I is net immobilization or fixation. Each loss term is itself stress-dependent, which is why poor synchrony is particularly costly under stress. The fate layer also includes the carrier: dissolution products, residual nanomaterial, and potential effects on soil biota must be tracked, since a formulation that improves NUE but accumulates persistent residues may trade one environmental problem for another (Lowry et al., 2019; Hofmann et al., 2020).

Methods developed for environmental remediation and toxicology can strengthen this fate layer. Data pipelines that link analytical chemistry to predictive toxicology (Aladegba & Ayinde, 2024) and conceptual models that couple exposure biomarkers with individual susceptibility (Aladegba et al., 2021) illustrate how residue concentrations can be connected to exposure and risk. Spatially explicit and data-driven models of subsurface contaminant migration (Azeez & Badmus, 2018; Lamidi & Olamide, 2018) and predictive frameworks for vapor intrusion risk (Azeez & Badmus, 2024b) offer templates for tracking nanomaterial and nutrient movement through soil and groundwater. Saline and marginal irrigation water is a further fate consideration: integrated physicochemical and bio-based treatment of produced water in arid environments, decentralized treatment systems and lifecycle risk assessment (Falegan & Aniebonam, 2023, 2024, 2022) are directly relevant where reclaimed water raises root-zone EC. Finally, gaseous losses such as nitrous

oxide need to be reported consistently, and improved methods for greenhouse gas inventories and carbon accounting (Azeez & Badmus, 2024a; Lamidi, 2023), greenhouse gas disclosure and ESG compliance obligations (Ominyi & Anichukwueze, 2022), automated ESG reporting (Abioye et al., 2023), and reviews of carbon removal technologies (Liadi et al., 2024) provide accounting conventions that nanofertilizer life-cycle studies can adopt.

3.7 Layer 6: Sensing, forecasting and adaptive management

The final layer recognizes that responsiveness can be engineered into the material, into the management system, or both. Soil moisture and temperature sensors, seasonal and sub-seasonal forecasts, and crop models can be used to choose among formulations with different gate settings before the season, to time application relative to forecast dry spells or heavy rain, and to adjust split applications. Over multiple seasons, data on SI and losses feed back into carrier redesign. The model therefore distinguishes intrinsic responsiveness (gates within the carrier) from extrinsic responsiveness (decisions informed by sensing and forecasts), and treats them as complementary.

The sensing component can build on rapid advances in low-power IoT. Systematic reviews of radio-frequency energy harvesting for energy-autonomous sensing (Asiedu & Quainoo, 2023a), simulations of maintenance-free, intermittently powered sensor networks (Asiedu & Quainoo, 2023b), and analyses of energy, reliability and latency trade-offs in green communication (Asiedu & Quainoo, 2024) are directly relevant to dense, unattended soil-moisture and temperature networks in fields without grid power, and modelling of impedance mismatch on wireless links (Quainoo et al., 2024) informs the design of robust field devices. Architectures for machine-learning-enabled energy management with IoT sensor networks (Kumuyi et al., 2024), AI-powered digital twins for predictive maintenance and fault detection (Shittu & Shittu, 2024; Shittu et al., 2023), tiered digital twins for resource-constrained sites (Komi & Adeniji, 2023), edge intelligence for resilient control (Komi & Ganiu, 2023), interpretable machine learning for early failure prediction (Komi & Adamolekun, 2021), IoT-enabled adaptive protection (Shittu et al., 2024), preventive maintenance programs for renewable systems (Yeboah et al., 2024), predictive maintenance and condition monitoring of critical infrastructure (Adaramola et al., 2018; Sunday et al., 2020), vibration-based monitoring (Omoegun et al., 2023) and sensor-based fault detection (Sunday & Omoegun, 2022) together suggest how a field-scale CRCR digital twin might be built and maintained. Because such networks become critical infrastructure in their own right, work on IoT security, adversarial machine learning in operational technology, and IT and OT convergence (Jimoh et al., 2023; Adebayo et al., 2022; Adegbite et al., 2022) is also relevant, as are cloud resource-scaling models for handling sensor data streams (Ahmed et al., 2020).

Forecasting and analytics provide the anticipatory element. Predictive modelling for renewable yield, hybrid deep learning for wind power, and equity-aware load forecasting (Ezeugwa et al., 2023; Komi, 2021, 2023) demonstrate methods transferable to seasonal stress forecasting, while statistical time-series models for long-range trend forecasting (Atakpa et al., 2024), big-data models for anticipating outbreaks at regional scale (Oparah et al., 2022), data-driven health surveillance and AI-based risk stratification for emergency preparedness (Ogunboye et al., 2023; Oparah et al., 2021), early-warning models for shortages of essential products (Eze et al., 2022), and data-driven frameworks for facility preparedness and disaster risk mitigation (Akinlolu et al., 2024) show how

sparse, noisy observations can be turned into early warnings. Data-driven digital transformation and performance intelligence models (Adelanwa et al., 2023, 2024b), AI-based decision support for resource planning (Adelanwa et al., 2024a), predictive early-warning analytics (Okwesa et al., 2024), real-time KPI tracking and performance dashboards (Tonoyan et al., 2024b; Ezeako et al., 2024), demand-forecasting models for supply chains and procurement (Aifuwa et al., 2020; Akin-Oluyomi et al., 2023c; Akin-Oluyomi & Akhigbe, 2023b), integrated AI and predictive analytics in supply chain management (Rukh et al., 2024), predictive models for vendor risk and cost (Tonoyan et al., 2024a), and econometric models of early technology adoption (Oteri & Chibwaye, 2022) can each be adapted to forecast nutrient demand, stress exposure and farmer uptake. Geospatial technologies complete this layer. Reviews and frameworks for UAV integration and transmission-line and corridor inspection (Dagodzo, 2018b, 2018c; Dagodzo & Ahiaeke Patrick, 2020), combined UAV, LiDAR and GIS corridor management (Dagodzo & Ahiaeke Patrick, 2021b), drone integration into enterprise GIS (Dagodzo & Ahiaeke Patrick, 2023a), GIS in asset management (Dagodzo & Ahiaeke Patrick, 2021a), encroachment detection (Dagodzo & Ahiaeke Patrick, 2022), deep-learning vegetation classification (Dagodzo et al., 2022), interpretation of LANDSAT and ASTER imagery (Dagodzo, 2018a), and UAV regulation in developing economies (Dagodzo & Ahiaeke Patrick, 2023b) map directly onto crop-stress scouting. GIS-enabled and geospatial decision frameworks (Ahiaeke Patrick et al., 2020, 2021; Tonoyan et al., 2022) show how such spatial data can be tied to procurement and site-selection decisions, which in agriculture translates into zone-specific formulation choice.

3.8 Outcome metrics

Four outcome metrics are defined. Nutrient use efficiency under stress, NUE_s, is computed conventionally for the stressed season. Loss intensity is the sum of L, V and E per unit yield. Yield stability is the coefficient of variation of yield across stress and non-stress seasons. A composite resilience index RI captures how much of the non-stressed nutrient performance is retained under stress:

$$RI = (NUE_s / NUE_{ref}) \cdot (Y_s / Y_{ref}) \quad (12)$$

where Y is yield and the subscript ref denotes a non-stressed reference. An RI close to 1 indicates that the formulation preserves both efficiency and productivity under stress. Table 2 lists the principal model variables, their units and suggested measurement approaches.

Table 2. Principal CRCR model variables, parameters and measurement approaches

Symbol	Definition	Units	Measurement or estimation
θ, T, EC, pH	Root-zone moisture, temperature, salinity and pH	$m^3\ m^{-3}$, °C, $dS\ m^{-1}$, unitless	In-situ sensors; soil sampling; weather-driven soil models
M_0	Nutrient loading of the carrier	$g\ kg^{-1}$ product	Elemental analysis of formulation
k_0, n	Reference release constant and release exponent	d^{-1} (or d^{-n}), unitless	Release assays at reference conditions

Symbol	Definition	Units	Measurement or estimation
Q_{10}	Temperature sensitivity of release	unitless	Release assays at three or more temperatures
θ_c, β_θ	Moisture gate threshold and steepness	$m^3\ m^{-3}$, unitless	Soil-incubation release across a moisture gradient
α_{EC}	Ionic sensitivity of release	$(dS\ m^{-1})^{-1}$	Release in electrolyte series matched to saline soils
$D_p(t)$, $\psi(S)$	Potential demand and stress modifier	$kg\ ha^{-1}\ d^{-1}$, unitless	Sequential biomass and tissue nutrient sampling; crop models
SI	Synchrony Index between release and demand	unitless (0 to 1)	Computed from R(t) and D(t)
L, V, E	Leaching, volatilization and gaseous losses	$kg\ ha^{-1}\ d^{-1}$	Lysimeters; chambers; isotope tracing (^{15}N)
RI	Resilience index	unitless	Paired stressed and reference trials

3.9 Testable propositions

The CRCR model generates the following propositions, each of which can be tested empirically. They are summarized with suggested test designs in Table 3.

Table 3. Testable propositions derived from the CRCR model

No.	Proposition	Suggested test design
P1	Under stress, SI is a stronger predictor of NUE and loss intensity than total release duration or mean release rate.	Compare multiple formulations across managed stress treatments; regress NUE on SI and on conventional release metrics.
P2	Formulations with $Q_{10} > 2$ and no thermal compensation will show lower RI under heat stress than heat-compensated formulations at equal dose.	Factorial trials of formulation by temperature regime in controlled environments and heat-wave field plots.
P3	Moisture-gated carriers reduce nitrate leaching and N_2O emission at rewetting relative to non-gated carriers.	Drying-rewetting soil column and chamber experiments with ^{15}N tracing.
P4	Ion-exchange carriers with $\alpha_{EC} > 0$ lose their NUE advantage over conventional fertilizer in saline soils.	Release and pot trials across an EC gradient with matched electrolyte composition.
P5	Gate effects combine approximately multiplicatively at low and moderate stress intensities, but interactions emerge at high intensities.	Response-surface experiments varying T and θ jointly.
P6	Biological (exudate-responsive) gates achieve higher SI under compound stress than abiotic gates alone.	Rhizobox experiments comparing gate types under combined heat and drought.

No.	Proposition	Suggested test design
P7	The NUE benefit of nanofertilizers over conventional controlled-release products is larger in stress-prone seasons than in favourable seasons.	Multi-season, multi-site field trials with stress characterization.
P8	Combining intrinsic gates with forecast-informed application timing yields higher RI than either alone.	Field trials crossing formulation type with decision-support use.
P9	Carrier persistence and residue accumulation are themselves stress-dependent, being slower under drought and faster under acidic or waterlogged conditions.	Multi-season residue tracking with matched stress histories.
P10	Release parameters fitted in water or buffer at a single temperature systematically overestimate field SI under stress.	Compare laboratory-predicted and field-observed release using buried-bag or tracer methods.

3.10 Illustrative simulation results

To check the internal logic of the model and illustrate its use, a simple simulation was constructed over a 100-day season that includes a 25-day drought (θ falling from 0.30 to 0.12 m^3 m^{-3}) with a superimposed 15-day heat wave (soil temperature rising by about 9 °C), followed by a rewetting event. Potential demand peaks at around day 55, reflecting a typical rapid-growth stage, and is reduced by the stress modifier ψ during drought and heat. Two carriers delivering the same total nutrient dose were compared. The conventional carrier follows first-order release with temperature sensitivity ($Q_{10} = 2$) and no gating. The climate-responsive carrier adds a moisture gate ($\theta_c = 0.20$), a heat-compensation term above 31 °C, and a root-exudate gate that activates as the root system expands. All parameters are hypothetical and chosen for illustration only; the results demonstrate model behaviour, not the performance of any real product.

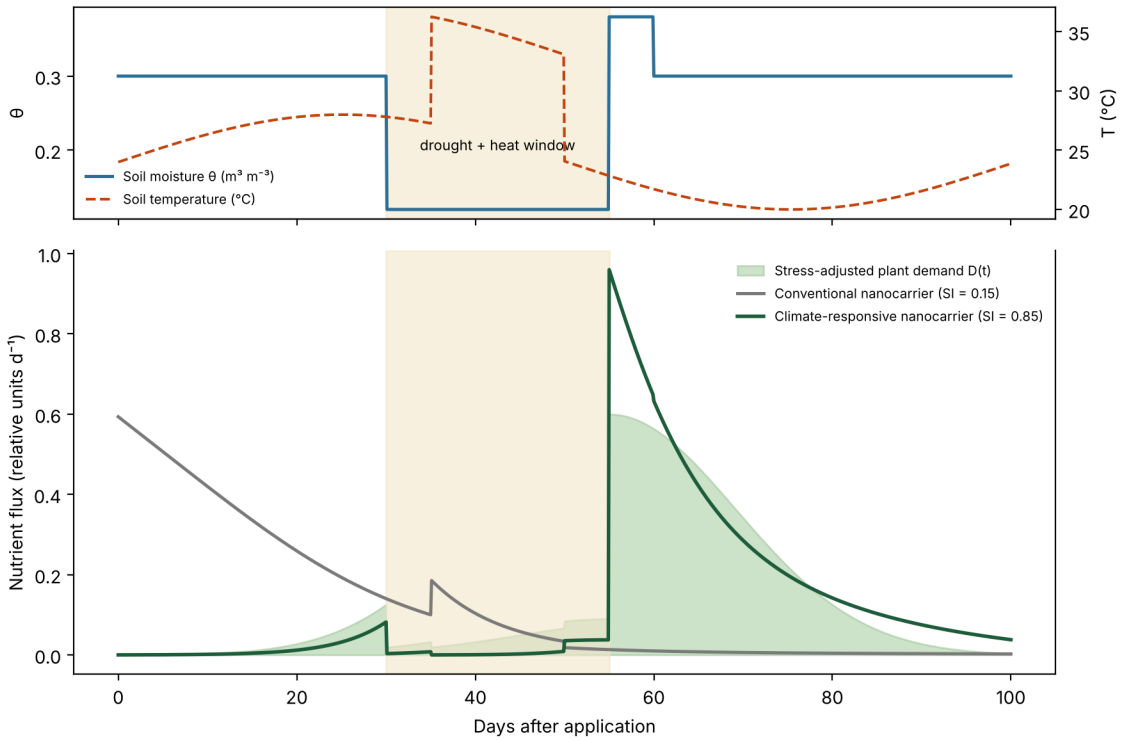


Figure 2. Illustrative CRCR simulation (hypothetical parameters). Upper panel: imposed soil moisture and temperature. Lower panel: release flux from a conventional and a climate-responsive nanocarrier compared with stress-adjusted plant demand. Both carriers deliver the same total nutrient dose.

The conventional carrier released about 82 percent of its nutrient before the drought began and well before peak demand, giving an SI of 0.15, with about 85 percent of its release occurring at times when release exceeded demand. The climate-responsive carrier withheld nutrient through drought and heat and released about 95 percent of its load after rewetting, when roughly 84 percent of demand also occurred, giving an SI of 0.85 with only about 15 percent of release in excess of demand. The simulation also exposes a design risk: the responsive carrier produces a sharp release peak immediately after rewetting that briefly exceeds demand. In the field this is the window of highest leaching and denitrification risk. Within the CRCR framework this is addressed by using a less steep moisture gate, a metered post-gate release law, or a biological gate that ramps with root activity, and it illustrates why the model treats stress transitions as a primary design constraint.

3.11 Stress-specific design logic

The following subsections interpret the CRCR model by applying it to the principal stress scenarios. The discussion then examines what the illustrative simulation reveals and situates the model within existing work on controlled-release and nano-enabled fertilizers.

The model implies that there is no single best release rate. Instead, the desirable gate configuration depends on how each stressor shifts the balance between release, demand and loss. The CRCR logic is applied here to the five principal stress scenarios.

3.11.1 Drought

During drought, demand falls (ψ declines as growth slows), the root's ability to acquire nutrient falls (h(θ) declines), and released nutrient accumulates in the soil around the carrier. The greatest risk is not during the drought itself but at rewetting, when accumulated nutrient and a burst of microbial activity coincide with renewed drainage. The model therefore favours a steep moisture gate with a threshold θ_c set above the level at which roots can acquire nutrients, so that nutrient remains protected within the carrier during drought. It also favours a release law that is metered on rewetting rather than one that releases the backlog immediately, since an instantaneous pulse can exceed recovery demand.

3.11.2 Heat

Heat accelerates diffusion and dissolution, so conventional carriers release faster at the very time heat-stressed crops may reduce growth. The CRCR design target is a temperature response that is flat or declining above a crop-specific heat threshold. This can be achieved with thermo-responsive components that densify above a transition temperature, or with dense inorganic coatings whose release has a low activation energy. Because ammonia volatilization rises with temperature, heat-compensated release of urea-based nitrogen also reduces gaseous losses.

3.11.3 Salinity

Salinity creates two problems. First, high concentrations of competing ions accelerate release from ion-exchange carriers, producing a positive α_{EC} that dumps nutrient into a soil where uptake is already impaired. Second, salinity alters the nutrient ratios that crops need, especially potassium-to-sodium and calcium-to-sodium balance. The design target is an α_{EC} near zero for the primary nutrient combined with co-delivery of potassium, calcium or silicon to support ionic homeostasis. Carriers such as LDH, which are attractive for anion delivery, require explicit testing in electrolyte solutions representative of saline soils.

3.11.4 Waterlogging

Under saturation, nitrate is rapidly lost through leaching and denitrification, and root uptake is suppressed by hypoxia. The model indicates that nitrogen release should be throttled under saturation, for example by hydrophobic or redox-sensitive coatings, and that co-formulation with nitrification inhibitors may be more effective than release control alone. For phosphorus, the main concern shifts to dissolved and particulate losses in runoff.

3.11.5 Compound and sequential events

Real seasons combine stresses, such as heat with drought, or drought followed by intense rainfall. Because gates combine multiplicatively in Equation 2, a carrier with both a moisture gate and a heat-compensation term will hold nutrients more strongly in hot, dry periods than either gate alone. Compound events also make transitions more abrupt, so the model places particular weight on controlling release during the hours to days after a stress ends. Biological gates triggered by root exudates are attractive under compound stress because they respond to the plant's own signal of renewed activity, which integrates all stresses at once.

3.12 Interpreting the simulation results

The simulation in Section 3.10 makes three points that matter beyond its hypothetical parameters. First, a carrier can be "slow release" in the conventional sense and still be badly mistimed: the conventional carrier released most of its nutrient before demand rose, which under field conditions would expose that nutrient to leaching, immobilization and gaseous loss. Second, gating can change the timing of supply without changing the dose, which is why SI is a more informative performance measure than release duration. Third, gating creates its own risk at stress transitions. The sharp post-rewetting peak shows that a gate which simply opens and closes can concentrate supply into a short window, so the design of the release law after the gate opens is as important as the gate itself.

3.13 Position relative to existing frameworks

Existing work on controlled-release fertilizers has focused on extending release duration and reducing the number of applications (Shaviv, 2001; Trenkel, 2010; Azeem et al., 2014), while reviews of nano-enabled agriculture have emphasized targeted delivery, responsiveness and the need for fair comparisons with conventional products (Kah et al., 2018; Lowry et al., 2019; Kah et al., 2019; Gilbertson et al., 2020). The CRCR model builds on both strands but differs in three ways. It makes climate stress the organizing design driver rather than a background condition; it evaluates release against stress-adjusted demand rather than against time; and it treats the fate of the carrier, not only the nutrient, as part of performance. In doing so it connects material design choices directly to the resilience outcomes that matter for farmers and regulators.

3.14 Trade-offs and design tensions

Responsiveness is not free. Each added gate increases formulation complexity and cost, and gates tuned for one stressor may perform poorly under another, for example a moisture gate that protects nutrients during drought may also delay supply in a cool, wet spring. Highly specific carriers also risk being poorly matched to the variable conditions of a given season, so there is a tension between optimizing for the expected stress profile of a location and maintaining robust performance across years. The model suggests that biological gates and the combination of intrinsic and extrinsic responsiveness are the most promising ways to manage this tension, because they allow supply to follow the crop rather than a single forecast variable.

3.15 Implications

3.15.1 For research and material design

The model reframes the material-design question from "how slowly can nutrient be released?" to "how should release respond to each stressor?" This invites a modular design approach in which carriers are assembled from components that each control one gate. It also gives materials scientists a target that agronomists can measure, namely SI under defined stress scenarios, and it clarifies which properties of a carrier must be reported for its climate performance to be predicted.

3.15.2 For agronomic practice

For practitioners, the model suggests that formulation choice should be matched to the dominant climate risk of a location and season. In semi-arid systems where dry spells followed by intense

rain are common, moisture-gated carriers with metered rewetting release would be prioritized. In hot lowland systems, heat-compensated nitrogen carriers may reduce volatilization. In salinizing irrigated systems, carriers with low ionic sensitivity and supporting potassium and calcium would be preferred. Forecast-informed timing can amplify these benefits.

Energy is an under-appreciated part of this picture. Nitrogen fertilizer production is tied to natural gas, so risk-based reliability engineering for natural gas infrastructure (Asibor & Isong, 2019), hydrogen as an energy carrier (Shittu et al., 2019), CO2 utilization strategies (Ijiga et al., 2023a) and renewable fuels such as biodiesel blends (Bello et al., 2023) bear on the carbon footprint of carrier manufacture and nutrient supply. Solar power for small-scale manufacturing and optimized load distribution for hybrid solar installations (Sunday & Omoegun, 2018, 2019), hybrid solar-diesel microgrids for underserved communities (Ijiga et al., 2023b), portfolio optimization for solar, wind and storage (Ilesanmi et al., 2024), smart-grid and distributed-energy control architectures (Adenuga, 2022; Komi & Adamolekun, 2022), peer-to-peer renewable microgrids (Shittu et al., 2021), co-optimized solar microgrids (Komi & Adeniji, 2020), lessons from solar deployments in emerging markets and large-scale solar programs (Amayo et al., 2024; Yeboah & Ike, 2020), energy-efficient logistics (Opara et al., 2024), and the wider economic, environmental and social impacts of renewable integration (Joseph & Uzondu, 2024b) indicate how local production of nanocarriers and powered sensing could be made viable in off-grid farming regions.

3.15.3 For smallholder and climate-exposed regions

Many smallholder systems in sub-Saharan Africa and South Asia face high rainfall variability, frequent dry spells, and limited capacity to adjust fertilizer application within the season (Bindraban et al., 2015). In such systems, intrinsic responsiveness built into the product may be more valuable than extrinsic responsiveness that depends on sensors and advisory services. At the same time, cost, local manufacturing capacity, product quality assurance, and farmer access to information are decisive. The CRCR model can help prioritize low-cost carrier chemistries, such as clay, biochar and hydroxyapatite composites derived from local materials, for the stressors most relevant to a region, and it highlights the need for evidence generated in these environments rather than extrapolated from temperate trials.

Equity and adoption deserve explicit attention. Research on the energy transition shows that no single financing instrument reaches the poor (Komi & Adeniji, 2024a) and that just transitions require skills mapping and attention to displaced livelihoods (Komi & Adamolekun, 2024). Community trust has been modelled as a measurable variable that predicts whether infrastructure projects endure (Komi, 2024; Komi & Adeniji, 2024b). Work on rural telehealth adoption and its role in bridging rural-urban disparities (Fapohunda et al., 2023; Oparah et al., 2024a), socioeconomic inequities in rural service delivery (Akinse et al., 2023), change management in digital transformation (Eyetsemitan et al., 2023), the adoption gap that undermines supply chain AI (Ogundairo & Ayivi-Donkor, 2024), persona research as a driver of technology adoption (Ukadike, 2024), and determinants of digital payment adoption in Sub-Saharan Africa (Agyei et al., 2019) all suggest that nanofertilizer uptake will depend on affordability, trust, usability and the distribution of benefits. Studies of locally sourced and renewable materials for low-income housing (Nwafor et al., 2019b; Uduokhai et al., 2024b) and system-dynamics modelling of circular economy

integration in African industry (Uduokhai et al., 2024a) further suggest that carrier matrices sourced from local clays, residues and minerals could lower costs while building regional manufacturing capacity.

3.15.4 For regulation and policy

Regulators currently lack consistent criteria for nanofertilizer claims (Hofmann et al., 2020). The CRCR model suggests that efficacy claims should be qualified by the stress conditions under which they were demonstrated, and that environmental assessment should cover carrier fate under the stresses a product is marketed for. Policy instruments that reward reduced nitrogen losses or improved NUE could use SI and RI as performance indicators, linking fertilizer innovation to national climate adaptation and mitigation commitments.

Governance models from regulated sectors can inform this agenda. Pharmaceutical supply chain governance that integrates environmental risk management (Eze et al., 2023), cross-border regulatory harmonization for African markets (Eze et al., 2024a), automated risk assessment for regulatory deliverables (Uchechi & Ominyi, 2020), real-time compliance pipelines and data governance (Uchechi et al., 2022), AI-assisted compliance monitoring and responsible AI governance for automated decisions (Ominyi et al., 2024; Ominyi & Anichukwueze, 2024), quantitative models of compliance risk in emerging economies (Akomolafe et al., 2023), regulatory reform through policy advocacy (Uchechi et al., 2019), public health governance and data-driven policy enforcement (Anioke & Atima, 2023a, 2023b), budget compliance and statutory reporting in Sub-Saharan Africa (Dogbatsey & Ebhojie, 2018), and compliance frameworks for technology transfer between developed and emerging markets (Jones & Ominyi, 2023) illustrate how nanofertilizer oversight and subsidy programs could be made both rigorous and workable. On the procurement side, ESG-integrated and sustainable procurement models (Okojie et al., 2020; Efobi et al., 2022a), ESG adoption in SME supply chains (Akinleye, 2023), green procurement strategies (Akin-Oluyomi et al., 2023b), supplier sustainability metrics (Akin-Oluyomi et al., 2023a), regulatory-compliant procurement in high-risk environments (Okonkwo et al., 2021b), supplier risk assessment in international procurement (Akin-Oluyomi et al., 2023d), green bonds and ESG financing (Sakyi et al., 2024), predictive emissions monitoring for ESG planning (Okojie et al., 2023), and decision frameworks for reconciling chemical safety with circular-economy goals (Okojie & Abioye, 2020) provide tools for public programs that purchase and distribute fertilizer. Distribution itself depends on digital supply chain governance, materials readiness, ERP-enabled logistics, IT and supply chain integration, agile digital transformation with embedded risk controls, lean supply chain optimization, supplier relationship management, supply chain leadership and quality governance, supply chain risk management, and port logistics efficiency (Okonkwo et al., 2024a, 2021a, 2024c, 2023, 2020; Mbonu et al., 2020; Efobi et al., 2022b; Ike et al., 2022, 2021; Akin-Oluyomi & Akhigbe, 2023a, 2022; Agbabiaka et al., 2019). Environmental practice in safety management and environmental compliance frameworks (Obogo et al., 2024b, 2024a) are relevant to the handling and disposal of nanomaterial products.

3.15.5 For capacity building and education

Designing, testing and using climate-responsive nanofertilizers requires a workforce that combines materials science, agronomy, data science and extension skills. Industry-academia collaboration

models for modernizing technical learning centres (Nwangwu et al., 2019) are relevant here, as is the integration of AI and machine learning into STEM education, interdisciplinary curriculum models, strategies for bridging the digital divide, and digital transformation in education (Joseph & Uzondu, 2024d, 2024c, 2024a; Joseph et al., 2024). AI-enabled education frameworks designed for African contexts (Seun et al., 2024) and offline-first and data-informed digital learning platforms for low-connectivity environments (Unamma et al., 2018; Orise & Niniola, 2020) indicate practical routes for training extension agents and farmers to interpret sensor data and select formulations.

3.16 Limitations

Several limitations should be acknowledged. The model treats the root zone as homogeneous, whereas nutrient release and uptake are highly heterogeneous at the scale of granules, aggregates and the rhizosphere. The multiplicative independence of gates is an assumption that may fail at high stress intensities, and P5 is stated precisely to test it. Plant demand is represented through a simple stress modifier rather than a full physiological model, and stress legacy effects across growth stages are not explicitly represented. Microbial interactions with nanocarriers, which can both degrade carriers and be affected by them, are represented only implicitly through the biological gate and the fate layer. The illustrative simulation uses hypothetical parameters and should not be read as evidence of real-world performance. Finally, economic, social and regulatory factors that determine adoption are discussed but not formally modelled. These limitations define the research agenda set out in Section 3.17 rather than undermining the model's purpose as an organizing framework.

3.17 Future research

3.17.1 Validation and operationalization roadmap

Because the CRCR model is conceptual, its value depends on whether its layers can be parameterized and its propositions tested. A four-phase roadmap is proposed (Table 4).

Table 4. Staged validation roadmap for the CRCR model

Phase	Activities	Key outputs	Linked layers
1. Laboratory	Release assays across temperature, moisture, ionic strength and pH gradients in soil (not only water); carrier characterization	k_0, n, Q_{10}, gate parameters; stress-sensitivity profiles	L2, L3
2. Controlled environment	Pot and rhizobox trials under managed drought, heat, salinity and waterlogging; ^{15}N tracing	Demand curves, $\psi(S)$, SI, partial mass balances	L3, L4, L5
3. Field	Multi-site, multi-season trials across climate gradients; rainout shelters and heat chambers; lysimeters and gas chambers	NUE_s, losses, RI, yield stability; test of P1, P7, P8	L1 to L5
4. Integration and scaling	Couple CRCR with crop and soil models; sensor and forecast decision support; life-cycle and risk assessment	Decision rules; regional suitability maps; regulatory evidence	L5, L6

Three methodological recommendations follow. First, release testing standards for nanofertilizers should include at least a temperature series and a soil-moisture series in soil, so that gate parameters can be reported alongside reference kinetics. Second, field studies should report SI or the data needed to compute it, namely time-resolved release (for example by buried mesh bags or tracer recovery) and time-resolved crop uptake. Third, comparisons should be made against best-available conventional practice, including conventional controlled-release products and split application, rather than single doses of soluble fertilizer, as recommended by critical evaluations of the field (Kah et al., 2018).

Quality and governance of validation data also matter. Lessons from data integrity failures and controls in regulated life sciences (Aneke et al., 2023), risk-based decision-making in good manufacturing practice (Aneke & Adesemoye, 2020), and risk-based accelerated-approval models that balance speed, safety and evidence quality (Eze et al., 2024b) are applicable to nanofertilizer registration, where field evidence across stress conditions will take years to accumulate. Validation also depends on laboratory capacity: models for sustainable diagnostic laboratory infrastructure in resource-constrained systems, regulatory-compliant laboratory design, laboratory networks as public interventions, and infrastructure-driven expansion of testing access to rural regions (Aminu-Ibrahim et al., 2018, 2020; Ogbete et al., 2019; Aminu-Ibrahim & Ogbete, 2023) offer templates for regional soil, plant and nanomaterial testing services. Occupational exposure during formulation and field application should be managed using established approaches to data-driven safety risk control, continuous hazard monitoring, proactive hazard identification, safety training and incident prevention (Obriki & Arumosoye, 2018, 2023; Obriki et al., 2023, 2022; Obogo et al., 2021).

3.17.2 Priority research directions

Beyond the staged validation of the model, several research directions follow from the CRCR framework:

- **Standardized stress-response testing.** Develop and agree protocols for measuring gate parameters (Q_{10}, θ_c, β_θ, α_{EC}) in soil rather than water, so that formulations can be compared across studies.
- **Field measurement of synchrony.** Develop low-cost methods, such as buried mesh bags, tracer recovery and in-situ ion sensors, to measure release and uptake at the temporal resolution needed to compute SI in farmers' fields.
- **Biological and multi-gate carriers.** Design and test carriers that respond to root exudates or rhizosphere enzymes, alone and in combination with abiotic gates, under compound heat and drought.
- **Transition control.** Investigate release laws that meter supply after a gate opens, with the aim of avoiding the rewetting pulse identified in the simulation.
- **Spatially explicit and coupled modelling.** Extend the model from a homogeneous root zone to spatially explicit, multi-layer representations and couple it with established crop and soil models.

- **Carrier fate and long-term safety.** Track the persistence, transformation and biological effects of carrier residues over multiple seasons and stress histories.
- **Socio-economic and adoption studies.** Assess cost-effectiveness, farmer perceptions, willingness to pay and institutional arrangements for climate-responsive formulations, particularly in smallholder systems.
- **Policy and regulatory research.** Examine how SI, RI and stress-qualified efficacy claims could be built into fertilizer registration, subsidy and climate finance programs.

4. Conclusion

Climate change makes the timing of nutrient supply as important as its quantity. Nanofertilizers offer an unusual opportunity to engineer timing into the product itself, but that opportunity is largely unrealized because carriers are designed and tested under fixed, favourable conditions and their responses to stress are often misaligned with crop needs. The Climate-Responsive Controlled Release model developed in this paper provides a structured way to close that gap. It links climate stress to carrier gates, gates to release kinetics, release to stress-adjusted demand and environmental fate, and all of these to sensing and management feedback. Its central metric, the Synchrony Index, gives material scientists, agronomists and policy makers a shared, measurable target, and its resilience index expresses performance in terms of what is retained under stress. The stress-specific design logic, ten propositions and staged validation roadmap are intended to move the field toward nanofertilizers that are evaluated, and ultimately designed, for the climate in which they will be used.

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