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Performance and limitations of agricultural hydrogels: A systematic evaluation across soil, crop, and environmental applications

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Abstract

Research has largely focused on hydrogels because of their ability to absorb and release both water and bioactive compounds, and crosslinked polymer networks. As such, their application in water-saving technology, soil moisture retention, and slow release of biopolymers in fertilizers, pesticides, and oral veterinary drugs has great potential. The review also confirms that multiple factors such as the formulation chemistry, application dose, soil texture and ionic environment are important in determining whether a technology is beneficial or harmful, a finding that directly contradicts the universal benefit framing that is common in review literature. The release of biopolymers in fertilizers, pesticides, and oral veterinary drugs slowly in combination with kaolin, hydrogels, cellulose derivatives and low commercial polyacrylates, in the pest control context, contradict the assumption. Additionally, to the author's best knowledge, no hydrogels have yet met *in vitro* or *in situ* pastoral yield improvement smallholder farmers. The first proof-of-concept field scale trials are required, as well as evidence of multi-season trials. Absence of the dose response at farm scale and the controlled-release on design logic and evolutionary resistance. The second field recommendation is the economic analysis. The use of common eco-pest control in resistance literature of pest control alludes to resistance-selection. Controlled-release of bioactive compounds and water in the same formulation is possible, and field scale research is recommended. The second field recommendation is to validate the design logic of controlled-release. The third and fourth field recommendations are also multi-seasonal smallholder. The cited literature suggests hydrogels have a justification see Pharmaceuticals.

Keywords: Hydrogels; sustainable agriculture; controlled release; water use efficiency; chitosan; biopesticides; livestock health; soil management

Introduction

The upcoming years from now to 2050 will see an exponential demand for food worldwide because of an expected rise in population. Along with this demand, agricultural systems will be under even more duress due to increased water scarcity and soil degradation. Regions particularly affected by increased challenges in water availability, soil salinization, and degradation from synthetic fertilizer use, will see the greatest challenges during food production. The UN has set an objective for the 2030 Agenda of Sustainable Development that all of its member states will decrease their use of pesticides by half. They have also set calls for increased food production, less reliance on chemical antibiotics in livestock systems, and improved productivity in farming systems (Angon *et al.*, 2023; Clemente *et al.*, 2023) ^[8, 11]. To meet these objectives, there is a need for the development of new farming technologies which improve the efficiency of using available resources, reduce the need for chemicals, and satisfy the growing demand for food production. This objective is currently not achieved with any of the conventional farming technologies that cover the four aspects of crop, soil, pest, and livestock management. These technologies all have a need to increase crop productivity while simultaneously decreasing the need for chemicals.

Hydrogels are a type of polymer that can be natural, synthetic, or composites that have the ability to absorb and hold water. They can also release their water in a controlled manner. Controlled release can be attained through the use of hydrogels because their release can be

dictated by how much water is in the soil (i.e., soil water potential). As an example of their controlled release and absorption, hydrogels can release water and even air pockets in the soil gradually, decreasing or removing the occurrence of soil cracking.

Some hydrogels can also increase the load-bearing capacity of soil, allowing for more support of the soil. Overall, hydrogels can be more closely engineered and tailored to meet a variety of agricultural needs (Abasalizadeh *et al.*, 2020; Khan *et al.*, 2021) [1, 22].

Four key areas of soil hydrogels' growing significance in agronomy are water retention, productivity, pest control, and livestock health and nutrition. Superabsorbent soil hydrogels can be applied to coarse and degraded soils to increase water retention, reduce water losses through evaporation, and improve soil aggregate stability (Albalasmeh *et al.*, 2022; Rizwan *et al.*, 2021) [6, 31]. Incorporation of microgels in soil amendments increases water use and seedling establishment, and decreases fertilizer loss (Abdelghafar *et al.*, 2024) [2]. Because of its sustained-order mass transfer function, biopolymer-based nanoformulations and hydrogels can deliver fungicides and biopesticides with low pest control acuted and biocompatible systemic ecotoxicity (Kumar *et al.*, 2022, 2023; Wang *et al.*, 2022) [23, 24, 38]. Hydrogels are being researched as vehicles of intramammary therapeutic supplements, nutritional supplements, antimicrobials, and fat replacers for fortified foods of animal origin (Foggiaro *et al.*, 2022; Gayen *et al.*, 2025; Rajasekaran & Santra, 2015; Zhang *et al.*, 2022) [15, 17, 30, 39].

Despite this breadth of application, the existing literature is characterised by three structural limitations that constrain its practical utility. First, the dominant evidence base consists of laboratory and singleseason greenhouse experiments; multi-site, multi-season field trials are absent across all four subtopics (Kumar *et al.*, 2023; Smagin *et al.*, 2022) [23, 24, 34]. Second, review literature has systematically aggregated findings across chemically and functionally distinct formulations, obscuring the formulation-specific, dose-dependent, and context-dependent nature of hydrogel performance a heterogeneity demonstrated empirically by the observation that specific commercial and experimental products reduce water productivity, crop biomass, and antimicrobial efficacy below untreated controls under conditions directly relevant to their intended use (Costa *et al.*, 2022; Rajanna *et al.*, 2022; Somsesta *et al.*, 2024) [13, 29, 35]. Third, disciplinary siloing has prevented cross-sub-topic synthesis: the resistance-selection implications of sustained-release agrochemical delivery identified in entomological literature have not been engaged by any materials science paper proposing controlled-release hydrogel formulations (Siddiqui *et al.*, 2023) [33].

This systematic review addresses these limitations by providing an integrated, evidence-critical synthesis of hydrogel research across soil management, crop productivity, pest control, and livestock nutrition and health. Drawing on approximately 50 peer-reviewed studies, the review maps the established evidence base, identifies and adjudicates contested empirical and mechanistic claims, traces the intellectual development of the field's three most pervasive concepts, and ranks the most consequential research gaps by practical impact on field adoption. The review's central objective is to determine whether current evidence supports the deployment of hydrogel technologies as scalable inputs in sustainable agricultural systems, or whether the literature remains at proof-of-concept stage pending the multi-season field validation that no existing study has yet provided.

Soil Management

Mechanisms of Soil Water Retention Enhancement

The primary mechanism by which hydrogels improve soil water retention is the absorption of gravitational and capillary water into the polymer network during irrigation or rainfall events, followed by its gradual release to the rhizosphere as the surrounding soil dries and water potential gradients increase. (Rizwan *et al.*, 2021) [31] provides the most comprehensive treatment of this mechanism, describing superabsorbent hydrogels as functioning as miniature reservoirs capable of releasing up to 95% of stored water to plant roots under deficit conditions, while simultaneously reducing deep percolation and evaporative losses. Swelling capacities across reported formulations range from 70 g/g for crosslinked polyvinyl alcohol composites to 996 g/g for polyacrylic acid-based systems measured under distilled water conditions, with the degree of swelling governed principally by crosslinking density, polymer composition, and the ionic strength of the surrounding solution (Rizwan *et al.*, 2021; Smagin *et al.*, 2022) [34].

A critical refinement of the retention concept is introduced by (Jong *et al.*, 2025) [21], who demonstrate empirically that swelling capacity and water retention rate are decoupled properties that cannot be treated as interchangeable performance metrics. A cellulose-glycerol hydrogel achieving 3,562% swelling retained only 10.48% of absorbed water over 96 hours, while a cellulose-polyethylene glycol formulation with lower peak swelling of 2,697% retained 33.47% over the same period. This divergence was attributed to differences in mean pore diameter larger pores in the glycerol system permitted rapid evaporative loss despite high initial absorption. The practical implication is that optimisation of hydrogels for soil moisture applications requires simultaneous characterisation of both swelling degree and retention kinetics rather than reliance on maximum absorption figures alone.

Effects on Soil Hydraulic Properties

The relationship between hydrogel application and saturated hydraulic conductivity (K_{sat}) is nonmonotonic and formulation-dependent, constituting one of the more substantive empirical contradictions in this literature. (Abdelghafar *et al.*, 2024) [2] report that K_{sat} decreased consistently with increasing hydrogel application rate across clay, loamy sand, and sandy-clay soils, attributing this to gel swelling and progressive blockage of macropore drainage pathways. (Albalasmeh *et al.*, 2022) [6], testing a wider concentration range in sandy soil, found that K_{sat} initially increased peaking at 108 cm/hr at 0.04% hydrogel concentration before declining at higher doses. This biphasic response, absent from the narrower concentration range examined by (Abdelghafar *et al.*, 2024), suggests that low-dose hydrogel application may temporarily enhance drainage before swelling sufficient to impede pore connectivity is achieved. These two positions are not reconcilable from available data, as they reflect different concentration ranges, soil textures, and experimental designs.

(Smagin *et al.*, 2022) [34] contribute a theoretically grounded challenge to the prevailing optimisation logic, demonstrating mathematically that sandy soils with total water capacity below 40% by mass cannot accommodate hydrogels with swelling degrees exceeding 600 kg/kg at agronomically cost-effective doses of approximately 0.1% by weight. Ultra-high-swelling formulations lose structural integrity under soil pore compression and risk viscous migration through the profile, rendering their laboratory-measured absorption capacity unrealisable under field conditions. (Smagin *et al.*, 2022)

propose a deliberate reduction of peak swelling to the 500–600 kg/kg range through increased crosslinker dosage as the engineering response to this constraint.

Performance across Soil Types

Soil texture modulates hydrogel performance in a manner that produces directly conflicting management recommendations depending on the metric selected. (Albalasmeh *et al.*, 2022) ^[6] report that the relative improvement in water use efficiency defined as the ratio of treated to control plot performance is greatest in sandy soil, because the low baseline water-holding capacity of coarse-textured substrates maximises the marginal benefit of hydrogel addition. (Abdelghafar *et al.*, 2024) ^[2], measuring absolute crop productivity rather than relative improvement, find that clay soil produced significantly higher lettuce fresh weight, dry weight, and chlorophyll content than loamy sand or sandy-clay soil across all hydrogel application rates. These positions are mutually exclusive as general prescriptions: one recommends prioritising sandy soils for hydrogel deployment; the other identifies fine-textured soils as the context of highest absolute return. (Jong *et al.*, 2025) ^[21] extend this texture-dependency finding, demonstrating that cellulose hydrogels produced substantial moisture improvements in sandy and topsoil profiles but failed to significantly enhance moisture content in clayey soil with three of four plasticiser formulations tested.

Saline and Chemically Stressed Soils

The performance of hydrogels under saline conditions the dominant co-stressor in the arid regions where these materials are most actively promoted is directly contested within this literature. (Rizwan *et al.*, 2021) ^[31], synthesising multiple independent studies, characterises superabsorbent hydrogels as beneficial under saline conditions, citing evidence that gel application reduces effective salt concentration in the root zone and improves crop establishment under moderate electrical conductivity. (Costa *et al.*, 2022) ^[13] Provide the sharpest empirical counter-evidence: a commercial potassium acrylate-acrylamide hydrogel applied at 0.07% w/w reduced maize shoot and root dry biomass at all salinity levels tested, increased plant sodium uptake from 9 to 13 mg kg⁻¹, and decreased potassium content by 10–16 mg kg⁻¹, indicating ⁺ ⁺ ionic imbalance exacerbated rather than mitigated by the polymer. Critically, the same hydrogel applied at 2.8 times the tested dose produced positive outcomes in separately cited studies, confirming that the direction of effect under salinity is dose-dependent and cannot be generalised from either positive or negative single-dose findings.

The mechanism underlying ionic suppression of swelling is identified by (Rizwan *et al.*, 2021) ^[31] as charge screening dissolved cations, particularly divalent Ca²⁺ and Mg²⁺, neutralise anionic polymer sites, ⁺ ⁺ reducing osmotic pressure differentials and blocking absorption sites across successive wetting-drying cycles. (Merino *et al.*, 2023) ^[26] Quantify the magnitude of this effect for agar-based hydrogels, reporting a fivefold reduction in swelling from 2,720% in distilled water to 533% in tap water attributable to in situ crosslinking by mineral ions. This finding carries a methodological implication that pervades the soil management literature: laboratory swelling values measured in distilled water systematically overestimate field performance and cannot serve as reliable predictors of agronomic outcomes in mineral-rich irrigation environments.

Research Gaps Specific to Soil Management

Four research gaps specific to this sub-topic warrant priority

attention. The absence of multi-season field trials remains the most consequential: (Smagin *et al.*, 2022) ^[34] explicitly acknowledge that comprehensive field trials under real soil and climatic conditions are rare in this literature, and all performance claims currently rest on greenhouse or bench-scale experiments incapable of capturing UV degradation, freeze-thaw cycling, tillage interactions, or cumulative ionic effects across growing seasons. The long-term ecotoxicological fate of degradation products including potential nanoscale polymer fragments, residual monomers such as acrylamide, and metal ions from crosslinking agents has not been characterised in any study within this corpus; biodegradation is measured exclusively by bulk weight loss, which cannot distinguish complete mineralisation from persistent oligomeric accumulation (Merino *et al.*, 2023) ^[26]. The dose-response relationship under realistic ionic conditions remains systematically unmapped: (Costa *et al.*, 2022) ^[13] demonstrate that dose and salinity interact to reverse the direction of plant growth response, yet no study provides a full factorial dose-by-ionic-environment characterisation across soil textures. Finally, the soil microbial community response to hydrogel amendment has not been addressed as a direct object of study; the contradictory framing of microbial activity as either beneficial nutrient cycling (Ilyasov *et al.*, 2022) ^[20] or destructive polymer degradation requiring suppression (Smagin *et al.*, 2022) cannot be resolved without community-level microbiome characterisation across amendment timescales.

Crop Productivity

Hydrogel Effects on Crop Growth and Yield

The agronomic case for hydrogel application in crop production rests on the premise that improved soil moisture availability translates directly into measurable gains in plant growth parameters and harvestable yield. Across the empirical literature, this relationship is supported under moderate water deficit conditions but is neither universal nor formulation-independent. (Abdelghafar *et al.*, 2024) ^[2] report significant increases in lettuce fresh weight, dry weight, leaf number, and chlorophyll content across all hydrogel application rates in a two-season pot experiment, with the combination of 85% evapotranspiration replacement and 0.3% hydrogel application rate producing the highest water use efficiency without significant yield penalty relative to full irrigation. (Rajanna *et al.*, 2022) ^[29], conducting the only multi-season replicated field trial in the corpus, document that Pusa hydrogel at 2.5 kg ha⁻¹ increased wheat grain yield by 3–15% and soybean seed yield by 6–25% over untreated controls under rainfed and limited irrigation conditions across two complete cropping years. (El-diehy *et al.*, 2024) ^[14] extend these findings to extreme drought conditions, reporting that an ultra-absorbent hydrogel synthesised through cyclic hydrolysis improved wheat shoot length by 18%, root length by 43%, shoot fresh weight by 49%, and shoot dry weight by 51% relative to unhydrogel-treated controls under 100% drought stress induction.

Critically, these yield benefits are formulation-specific and do not extend uniformly across product classes. (Rajanna *et al.*, 2022) ^[29] document that kaolin-derived hydrogel applied at both 2.5 and 5.0 kg ha⁻¹ reduced crop water productivity and irrigation water productivity by 5–14% relative to the no-hydrogel control in the same field experiment a directly contradictory outcome produced by a different formulation under identical agronomic conditions. This intra-study contradiction is the single most consequential finding in the crop productivity sub-topic, demonstrating that the direction of hydrogel effect on yield is not a class property of hydrogel

materials but a function of specific polymer chemistry.

Water Use Efficiency

Water use efficiency (WUE), defined as crop yield or biomass per unit of water consumed, serves as the primary performance metric across the crop productivity literature, yet its measurement is neither standardised nor consistently applied. (Albalasmeh *et al.*, 2022) ^[6] operationalise WUE as the ratio of above-ground dry biomass to total applied irrigation water, and introduce the additional construct of relative WUE the ratio of treated to control plot efficiency to enable normalised comparison across soil types. (Patra *et al.*, 2022) ^[28] compile WUE improvements from over twenty independent studies without distinguishing between this formulation and at least three alternative definitions employed across the cited evidence base, creating an appearance of consensus that obscures fundamental metric incomparability.

The assumption that full irrigation maximises WUE is directly challenged by (Abdelghafar *et al.*, 2024) ^[2], who report that the highest WUE value of 10.01 kg m⁻³ was achieved at 85% evapotranspiration – replacement, while the lowest value of 8.61 kg m⁻³ was recorded under full irrigation. This finding that – mild deficit irrigation combined with hydrogel amendment outperforms full irrigation on a per-waterunit basis contradicts the implicit optimisation logic of (Patra *et al.*, 2022) ^[28], who present full-irrigation hydrogel studies as the primary evidence base for WUE improvement claims without flagging the deficit irrigation interaction. (Rajanna *et al.*, 2022) ^[29] introduce a further definitional complexity by distinguishing water productivity from irrigation water productivity, finding that both metrics were highest under rainfed conditions a result that mechanically follows from adding rainfall to the denominator of the irrigated plots, but which complicates straightforward claims about hydrogelmediated WUE enhancement under managed irrigation.

Controlled-Release Fertiliser Applications

The integration of hydrogels as controlled-release fertiliser carriers represents the most technically advanced and least empirically validated frontier within crop productivity research. Ahmad *et al.* (2023) ^[5] provide the most rigorous kinetic characterisation of this function in the corpus, demonstrating that a cellulose hydrogel synthesised from wastepaper released only 50.77% of loaded urea within one day, compared to 98.7% for free urea under identical conditions, with 74.71% released at 42 days in topsoil. Release was characterised as Fickian diffusion using the Korsmeyer-Peppas model with R² values exceeding 0.85, providing the only mechanistic kinetic framework for controlled nutrient release in this literature. (Ahmad *et al.*, 2023) ^[5] identify a burst-release effect at the initial stage attributable to high surface concentration gradients as a design limitation that partial undermines the slow-release claim, but do not conduct any plant growth experiment to determine whether the modified release profile translates to measurable agronomic benefit.

(El-diehy *et al.*, 2024) ^[14] partially bridge this gap by loading their ultra-absorbent hydrogel with 5% urea and measuring crop-level nitrogen outcomes, reporting shoot protein content increases of 18–32% and grain protein content increases of 10–21% across drought stress levels relative to control. However, their experimental design does not include an unfertilised hydrogel-only arm, making it impossible to attribute protein gains specifically to controlled nutrient release rather than to the hydrogel's water retention effect facilitating conventional

nitrogen uptake from bulk soil solution. The water-retention effect and the nutrient-release effect remain experimentally confounded in every crop-level study in the corpus. (Patra *et al.*, 2022) ^[28] situate this concept historically, noting that the association of fertiliser with hydrogel nanomaterials opened new avenues in crop production, and that nanofertilisers loaded within hydrogel nanoparticles allow slower nutrient release but the mechanism linking laboratory release kinetics to plant nitrogen status under field drought conditions is asserted rather than demonstrated in any single paper.

Performance across Crop Types

The crop productivity literature spans wheat, soybean, lettuce, and forage grasses across contrasting agroecological contexts, but no study within the corpus designs a cross-crop comparative experiment. (Rajanna *et al.*, 2022) ^[29] demonstrate that hydrogel response differs between wheat and soybean within the same field trial and under the same irrigation regime soybean under full irrigation showed near-zero or negative yield response to Pusa hydrogel, while wheat under the same conditions showed a positive response. (Barros *et al.*, 2024) ^[10], working with tropical forage grasses, report that a cashew gum-based natural hydrogel achieved equal or superior root dry biomass and leaf elongation rates compared to commercial polyacrylamide across four grass genotypes, extending the performance evidence base beyond arable crops to pasture systems and simultaneously demonstrating that a low-cost natural alternative can match synthetic product performance under greenhouse conditions.

Research Gaps Specific to Crop Productivity

Three research gaps are of particular consequence for this sub-topic. The mechanism linking controlled-release nutrient delivery in laboratory conditions to plant nitrogen uptake and grain yield under field drought remains undemonstrated in any single study: (Ahmad *et al.*, 2023) ^[5] provide the kinetic characterisation without crop response data, while (El-diehy *et al.*, 2024) ^[14] provide the crop response data without mechanistic separation of water and nutrient effects. Resolving this gap requires isotopically labelled nitrogen (¹⁵N-urea) loaded into hydrogel matrices with a water-only hydrogel control arm under matched drought stress conditions. The economic viability of hydrogel application at smallholder scale has been analysed in only one study: (Rajanna *et al.*, 2022) ^[29] report 12.97% higher economic returns from Pusa hydrogel at 2.5 kg ha⁻¹ in a wheat-soybean system, but this finding is – specific to a single Indian agroecological zone under government minimum support pricing and cannot be generalised to other crop types, water tariff structures, or income-constrained farming contexts. Finally, no study in the corpus tracks root architecture, canopy development, or yield components across a full growing season under hydrogel amendment single-timepoint measurements at anthesis, as employed by (Rajanna *et al.*, 2022), cannot resolve whether root morphology responses observed midseason persist to grain fill or reflect transient compensatory behaviour under temporarily improved moisture conditions.

Pest Control

Hydrogels as Pesticide Delivery Systems

The application of hydrogel matrices as pesticide delivery systems is motivated by two converging pressures: the regulatory mandate to reduce total agrochemical loading in agricultural environments, and the technical limitation of conventional formulations that release active ingredients rapidly, generating peak concentrations toxic to non-target organisms

while providing only brief residual protection against target pests. (Clemente *et al.*, 2023) ^[11] frame this dual imperative directly, noting that the UN 2030 Agenda's pesticide reduction targets cannot be met through prohibition alone and that controlled release of bioactive chemicals represents a technically viable pathway to maintaining crop protection efficacy at reduced total input volumes. Across the pest control literature, three principal delivery architectures are represented: nanoparticle-based polymer carriers, emulsion-based nanoemulsions, and macroscale hydrogel beads and matrices each characterised by distinct release kinetics, target organism profiles, and environmental persistence properties.

(Wang *et al.*, 2022) ^[38] provide the most direct demonstration of the non-target safety benefit of hydrogel encapsulation, quantifying that gelatin-encapsulated niclosamide reduced zebrafish mortality by an order of magnitude relative to equivalent concentrations of free niclosamide solution. At 0.5–1.0 mg/L, free niclosamide produced 100% zebrafish mortality within 20 minutes, while the gelatin formulation at the same concentration produced only 10–20% mortality at 96 hours. The authors attribute this reduction to the physical barrier imposed by the gel matrix, which attenuates peak concentration exposure while maintaining sustained molluscicidal activity against the target organism *Pomacea canaliculata* over periods of up to 20 days at 1.5% gelatin concentration. Pore density, governed by gelatin concentration, was identified as the primary determinant of release rate a structural analogue to the crosslinking density mechanism established across the broader hydrogel literature.

Controlled Release Mechanisms and Kinetics

The kinetic characterisation of pesticide release from hydrogel matrices is most systematically developed in the nanoformulation papers, where dialysis membrane methods and mathematical release modelling permit quantitative comparison against commercial benchmarks. (Kumar *et al.*, 2022) ^[23] demonstrate that chitosan-carrageenan nanoparticles loaded with mancozeb released only 42% of their payload within two hours, compared to 98% for commercial mancozeb under identical conditions, with sustained release extending across a ten-hour window. (Kumar *et al.*, 2023) ^[24], employing guar gum nanoemulsions as an alternative carrier, achieved comparable sustained release over eight hours against the same commercial benchmark. Both studies identify the dialysis membrane as a proxy for soil diffusion barriers, and both use the quantitative differential 98% versus 42–43% release at two hours as the primary evidence for controlled-release superiority over conventional formulations.

(Saruchi *et al.*, 2023) ^[32] extend kinetic characterisation to an aloe vera-acrylic acid copolymer system loaded with dichlorvos, identifying non-Fickian anomalous diffusion as the operative release mechanism with a diffusion exponent of $n = 0.99$. This characterisation, in which release rate is governed by polymer matrix relaxation time rather than concentration gradients alone, distinguishes their system mechanistically from the Fickian diffusion identified by (Ahmad *et al.*, 2023) ^[5] in the crop productivity context and indicates that release mechanism varies with polymer architecture in ways that preclude universal kinetic modelling across hydrogel types. (Clemente *et al.*, 2023) ^[11] characterise glycoalkaloid release from sodium alginate and carboxymethyl cellulose hydrogel beads, reporting only 2.8% cumulative release in aqueous conditions over 21 days a retention figure the authors themselves acknowledge is likely unrepresentative of soil conditions where erosion and matrix disintegration mechanisms operate alongside diffusion.

Biopesticide Applications: Chitosan and Plant-Derived Compounds

Chitosan occupies a structurally unique position in the pest control literature as simultaneously a carrier matrix, a direct antifungal agent, and a plant immune elicitor properties that distinguish it from all other polymer carriers reviewed. (Hassan & Chang, 2017) ^[19] provide the foundational dual-mechanism framework, documenting that chitosan inhibits fungal and bacterial pathogens through electrostatic disruption of negatively charged microbial cell membranes by protonated amino groups, while simultaneously inducing host plant defence responses including pathogenesis-related protein synthesis, peroxidase and polyphenol oxidase activation, phytoalexin accumulation, and systemic acquired resistance. (Kumar *et al.*, 2022) ^[23] confirm intrinsic antifungal activity independent of chemical payload, finding that blank chitosan-carrageenan nanoparticles without mancozeb achieved up to 50% inhibition of *Alternaria solani* *in vitro* evidence consistent with the direct antimicrobial pathway described by (Hassan & Chang, 2017).

(Clemente *et al.*, 2023) ^[11] extend the biopesticide concept to plant-derived glycoalkaloids, encapsulating α -tomatine extracted from tomato leaves in alginate and carboxymethyl cellulose matrices and demonstrating p H-dependent bioavailability the compounds are inactive at p H 4 but active at p H 7 and above, introducing a biochemical condition on release that synthetic pesticide formulations do not face. This p H dependency requires that the hydrogel matrix maintain a compatible microenvironment for biological activity, a design constraint absent from carrier systems loaded with synthetic active ingredients whose efficacy is p H-independent.

(Merino *et al.*, 2023) ^[26] present a directly contradictory outcome for limonene-loaded agar hydrogels, reporting complete absence of antibacterial or antifungal activity against *Pseudomonas syringae* pv. tomato DC3000 and *Fusarium solani* f. sp. *eumartii* despite prior literature documenting limonene activity in aqueous media. The authors attribute this null result to immobilisation of the terpene within the hydrogel network reducing bioavailability at target concentrations a finding that directly challenges the premise, implicit in (Clemente *et al.*, 2023) ^[11] and (Saruchi *et al.*, 2023) ^[32], that volatile or hydrophobic bioactive compounds retain antimicrobial efficacy when physically entrapped in a polymer matrix. The contradiction is formulation-specific but its implication is general: hydrogel encapsulation does not preserve the biological activity of all compound classes, and activity screening in aqueous solution cannot predict activity from gel-encapsulated delivery.

Performance against Specific Pest and Pathogen Species

Efficacy data across the nanoformulation papers spans four fungal pathogens *Alternaria solani*, *Sclerotinia sclerotiorum*, *Alternaria alternata*, and *Rhizoctonia solani* and one aquatic pest species. (Kumar *et al.*, 2022) ^[23] report disease control efficacy of 79.4% for chitosan-carrageenan nanoformulations against *Alternaria solani* under pot conditions, exceeding commercial mancozeb at 76% for the same organism, and 77.2% against *Sclerotinia sclerotiorum* versus 68% for the commercial product. (Kumar *et al.*, 2023) ^[24], using guar gum nanoemulsions against the same pathogen set, report disease control efficacy of 68.5–70.4% described as comparable to commercial mancozeb but not consistently superior across all target species. The directional claim of nanoformulation superiority is thus supported for specific pathogen-carrier combinations but not established as a universal property of the

delivery architecture.

The molecular weight dependence of chitosan efficacy introduces a further complication that neither nanoformulation paper addresses. (Hassan & Chang, 2017) ^[19] document that the relationship between molecular weight and antifungal activity reverses across pathogen species: low molecular weight chitosan outperforms high molecular weight against *Rhizopus stolonifera*, *Botrytis cinerea*, and *Penicillium expansum*, while high molecular weight chitosan is superior against *Fusarium oxysporum*, *Alternaria solani*, and *Valsa mali*. This species-dependent inversion means that optimal chitosan formulation for mixed-pathogen field conditions cannot be derived from single-pathogen laboratory screening a constraint that neither Kumar paper acknowledges in reporting its efficacy results.

Research Gaps Specific to Pest Control

Five research gaps require priority attention in this sub-topic. Field-scale validation is entirely absent: (Kumar *et al.*, 2023) ^[24] explicitly state that large-scale field trials and *in vivo* toxicity studies are mandatory before commercial application, yet no paper in the corpus reports open-field efficacy or environmental persistence data under agronomic conditions. The resistance-selection paradox of slowrelease delivery remains unaddressed by every controlled-release paper in the corpus: (Siddiqui *et al.*, 2023) ^[33] identify sustained-release formulations as a documented resistance-inducing operational factor through prolonged sub-lethal selective pressure, yet this finding is absent from the reference lists of all five controlled-release papers a disciplinary blind spot with direct implications for the long-term utility of the technology. The biochemical mechanism separating chitosan's direct antimicrobial effect from its host resistance elicitation pathway has not been experimentally resolved in any study: (Hassan & Chang, 2017) ^[19] explicitly state that the mode of action remains unclear, and no paper designs an experiment capable of disaggregating the two pathways under matched conditions. Non-target ecological safety has been assessed exclusively against Vero monkey kidney cell lines and zebrafish no study tests effects on beneficial soil invertebrates, pollinators, or soil microbial functional guilds, all of which represent regulatory requirements for commercial pesticide registration. Finally, the long-term environmental fate of nanoparticle carrier materials and their degradation products in agricultural soils has not been characterised in any study, despite acknowledged concerns about polymer fragment accumulation and metal ion ecotoxicology at repeated commercial application rates (Kumar *et al.*, 2022; Rajasekaran & Santra, 2015) ^[23, 30].

Livestock Nutrition and Health

Hydrogels as Nutrient Delivery Systems in Animal Production

The application of hydrogel matrices as nutrient delivery vehicles in livestock production spans two distinct functional objectives: the provision of hydration and bioavailable nutrition during critical developmental windows where conventional feed access is delayed or restricted, and the encapsulation of minerals, vitamins, and probiotics to improve bioavailability and gastrointestinal transit survival. (Uyanga *et al.*, n.d.) ^[37] provide the broadest synthetic treatment of this application domain, characterising hydrogels as capable of simultaneously enhancing water retention in feed, protecting sensitive bioactive compounds from gastric acid degradation, and releasing nutrients in synchrony with intestinal absorption capacity a multi-function delivery profile that no single conventional feed additive achieves.

The most direct experimental test of hydrogel nutritional delivery in poultry is provided by (Ács *et al.*, 2025) ^[3], who conducted a controlled trial across 1,120 Ross 308 broiler eggs to evaluate the effect of Hydrogel® provision a commercially available post-hatch supplement during a 48-hour feed access delay representative of standard commercial hatchery transit conditions. Chicks receiving Hydrogel® supplemented with methionine showed upregulated interleukin-2 gene expression at days 21 and 35 post-hatch comparable to immediately-fed controls, and improved lymphocyte and eosinophil counts relative to unsupplemented delayed-feeding groups. These findings suggest that hydrogel-delivered methionine partially mitigates the immunological consequences of post-hatch feed deprivation at the molecular level. However, (Ács *et al.*, 2025) report that malondialdehyde concentration a marker of oxidative stress was not significantly affected by any treatment, including the hydrogel-methionine group, and that final body weight in all delayed-feeding treatments remained significantly lower than immediately-fed controls at day 35. The authors conclude explicitly that no early feeding method tested, including hydrogel supplementation, can replicate the growth outcomes of immediate conventional feed access a finding that establishes a ceiling on the functional utility of hydrogel nutritional supplements in commercial poultry management.

(Gelaye, 2024) ^[18] extends the nutrient delivery concept to nanoparticle-encapsulated minerals, reviewing evidence that copper and zinc nanoparticles delivered via hydrogel vehicles improve bioavailability at doses substantially lower than conventional mineral supplementation, thereby reducing the total mineral load entering the environment through animal excreta. This application directly addresses the environmental externality identified by (Rajasekaran & Santra, 2015) ^[30], who acknowledge that conventional copper and zinc supplementation at growth-promoting doses contributes to soil microbial toxicity through excretory accumulation while proposing that chitosan-mediated delivery at reduced doses resolves this without sacrificing antimicrobial or growth-promoting efficacy.

Antibiotic Alternative Applications

The framing of biopolymer hydrogels as vehicles for antibiotic-free livestock management constitutes the most clinically consequential and most contested application domain within this sub-topic. (Rajasekaran & Santra, 2015) ^[30] establish the foundational rationale, opening with the WHO's antimicrobial resistance warning and positioning their chitosan-copper-zinc hydrogel as a direct functional substitute for antibiotic growth promoters, targeting the same gut bacterial populations *Escherichia coli*, *Enterococcus faecalis*, *Staphylococcus aureus*, and *Lactobacillus fermentum* while achieving bactericidal activity at concentrations that produce negligible cytotoxicity in mammalian cell lines. Their *in vitro* data demonstrate reductions in target bacterial populations of 75–99.99% across species, with the chitosan matrix reducing metal salt cytotoxicity against RAW 264.7 macrophages from 92% cell killing to approximately 5% at equivalent zinc concentrations the most direct quantitative demonstration of matrix-mediated toxicity attenuation in the corpus.

(Uyanga *et al.*, n.d.) ^[37] synthesise the antibiotic-alternative framing at the broadest level, cataloguing hydrogel functions across direct antibacterial delivery, probiotic protection from gastric acid, wound healing facilitation, and nutrient encapsulation as a collective response to the regulatory prohibition of antibiotic growth promoters across multiple jurisdictions. However, a direct contradiction arises from the

same paper set: (Uyanga *et al.*, n.d.)^[37] characterise hydrogels as capable of enhancing water retention and improving growth performance under heat stress without qualification about their limits relative to conventional management, while (Ács *et al.*, 2025)^[3] provide experimental evidence that hydrogel supplementation produces statistically inferior growth outcomes compared to immediate conventional feeding under commercial conditions. These positions are mutually exclusive as general claims about hydrogel efficacy as a management substitute.

Veterinary Treatment Applications

The most clinically developed veterinary application of hydrogels in this corpus is intramammary infusion for bovine mastitis therapy. (Baipaywad *et al.*, 2022)^[9] characterise a poly (lactic-co-glycolic acid) hydrogel loaded with gallic acid as a sustained-release intramammary teat sealant designed to replace conventional long-acting antibiotic dry cow therapy, demonstrating that 48.9% of the gallic acid payload was released over seven days before transitioning to more gradual sustained release across a 30-day period. The therapeutic rationale is explicitly antibiotic substitution: the authors position their formulation against the current standard of care using long-acting antibiotics and demonstrate bacteriostatic activity against mastitis-relevant pathogens through cited minimum inhibitory concentration data. However, no *in vivo* bovine teat trial is reported, and the cytotoxicity data reveal that the formulation produced 18–20% reduction in L929 fibroblast cell viability attributable to residual N-methyl-2-pyrrolidinone solvent a finding the authors acknowledge but do not resolve at application-relevant concentrations.

(Zhang *et al.*, 2022)^[39] approach the same therapeutic target through a mechanistically distinct framework, conducting a seven-day intramammary infusion trial in twelve lactating dairy cows with subclinical mastitis using a matrine-chitosan hydrogel. Somatic cell count was significantly reduced by day seven, and 16S rRNA microbiome sequencing revealed decreased microbial diversity as measured by the Simpson index alongside increased relative abundance of Proteobacteria including *Pseudomonas* and

Ralstonia. Liquid chromatography-mass spectrometry metabolomics identified 74 differentially expressed metabolites including sphingolipids and glycerophospholipids consistent with anti-apoptotic and anti-inflammatory pathway activation. The authors conclude that the therapeutic mechanism operates through immunoregulation and microbiome remodelling rather than direct bactericidal action a mechanistic claim directly at odds with the delivery-vehicle bactericidal framework of (Baipaywad *et al.*, 2022)^[9]. Critically, (Zhang *et al.*, 2022)^[39] note that the same pattern of reduced microbial diversity was observed in the conventional antibiotic control group, suggesting that microbiome disruption may be an unavoidable consequence of any effective antimicrobial intervention regardless of agent type.

Performance across Livestock Species

The evidence base within this sub-topic spans poultry, dairy cattle, and ruminants, but no study designs a cross-species comparative experiment, and the methodological quality varies substantially across species contexts. (Ács *et al.*, 2025)^[3] provide the largest and most methodologically rigorous poultry trial in the corpus, with 1,120 birds across seven treatment groups followed to day 35. (Zhang *et al.*, 2022)^[39] provide the only *in vivo* dairy cattle therapeutic trial, with twelve animals across two treatment groups at a single farm over seven days a

sample size the authors themselves acknowledge as insufficient for population-level safety or efficacy inference. (Zubiría *et al.*, 2025)^[40] extend the application domain to ruminant parasite control, demonstrating *in vitro* that an agar-agar gel simultaneously carrying piperazine and levamisole anthelmintics alongside live *Mucor circinelloides* spores maintains full fungal viability in the presence of both antiparasitic compounds establishing biological compatibility as a prerequisite for combined curative-preventive delivery but providing no animal performance data. (Foggiaro *et al.*, 2022)^[15] address the food systems dimension, demonstrating that alginate-based emulsion hydrogels replacing pork backfat in burger reformulation improved nutritional composition indices including polyunsaturated to saturated fatty acid ratio, thrombogenicity index, and atherogenicity index while achieving acceptable sensory scores from an evaluation panel.

Research Gaps Specific to Livestock Health and Nutrition

Four research gaps require priority resolution in this sub-topic. No hydrogel formulation proposed for veterinary or nutritional application has been validated in a production-scale, multi-herd, longitudinal trial: (Zhang *et al.*, 2022)^[39] represent the closest approximation with twelve animals at a single farm, and (Ács *et al.*, 2025)^[3] follow 1,120 birds but only to day 35 under research rather than commercial management conditions. The mechanistic pathway by which chitosan-based hydrogels reduce somatic cell count in mastitis remains unresolved between direct bactericidal action and microbiome-mediated immunoregulation: (Zhang *et al.*, 2022)^[39] explicitly state this question requires further investigation, and no study in the corpus designs an experiment capable of decoupling the chitosan vehicle contribution from the active pharmaceutical ingredient contribution to therapeutic outcomes. The long-term environmental and food-chain fate of nanoparticle-loaded formulations specifically silver, copper, and zinc nanoparticles released through animal excretion has not been measured in any study despite explicit acknowledgement of the risk by both (Gelaye, 2024; Rajasekaran & Santra, 2015)^[18, 30]. Finally, no study measures whether observed benefits reduced somatic cell count, improved immune gene expression, microbiome compositional shifts persist beyond the active treatment window, leaving the durability of hydrogel-mediated therapeutic and nutritional outcomes entirely uncharacterised across all livestock species and application contexts.

Discussion

Cross-Cutting Themes across Sub-Topics

The synthesis of evidence across soil management, crop productivity, pest control, and livestock health reveals a field unified by a compelling theoretical premise but fragmented by methodological immaturity. Three structural patterns recur across all four sub-topics with sufficient consistency to constitute defining characteristics of the field rather than isolated disciplinary concerns.

The first is the systematic divergence between formulation-class claims and formulation-specific evidence. Across every sub-topic, review literature aggregates outcomes from chemically and functionally distinct hydrogel products into unified benefit narratives that individual empirical studies repeatedly contradict. (Patra *et al.*, 2022)^[28] present hydrogel WUE improvement as a class property; (Rajanna *et al.*, 2022)^[29] demonstrate that a kaolin-derived formulation reduces water productivity below the untreated control. (Uyanga *et al.*, n.d.)^[37] characterise biopolymer hydrogels as categorically safer than synthetic

alternatives; (Baipaywad *et al.*, 2022) ^[9] document measurable cytotoxicity from an FDA-approved synthetic formulation attributable to a solvent co-component rather than the polymer itself; (Jong *et al.*, 2025) ^[21] show that a natural cellulose derivative elevates soil electrical conductivity twelvefold through ionic release. The pattern is consistent: beneficial outcomes demonstrated for one formulation are routinely generalised to the category, obscuring the possibility empirically confirmed in multiple sub-topics that specific chemistries produce net-harmful outcomes under conditions directly relevant to their intended use. This aggregation bias is the field's most consequential analytical failure, and no future systematic review or meta-analysis can resolve it without formulation-stratified data that current primary studies do not provide.

The second cross-cutting pattern is the universal confinement of evidence to controlled laboratory and greenhouse conditions. (Smagin *et al.*, 2022) ^[34] identify this explicitly as a field-wide problem in soil management; (Kumar *et al.*, 2023) ^[24] acknowledge it as a prerequisite unmet in pest control; (Baipaywad *et al.*, 2022) ^[9] and (Rajasekaran & Santra, 2015) ^[30] frame their entire studies as proof-of-concept requiring animal-scale validation in livestock health; (Ahmad *et al.*, 2023) ^[5] provide kinetic characterisation without any crop experiment in crop productivity. This is not a gap in one sub-topic it is the universal evidentiary ceiling of the field. The practical consequence is that no agronomic or veterinary recommendation in this literature rests on evidence obtained under the conditions for which the recommendation is made.

The third pattern is disciplinary siloing that prevents cross-sub-topic knowledge transfer. The resistance-selection implications of sustained-release agrochemical delivery identified by (Siddiqui *et al.*, 2023) ^[33] in the entomological literature are absent from every controlled-release materials science paper in the pest control corpus. The microbiome disruption documented by (Zhang *et al.*, 2022) ^[39] in mastitis therapy mirrors the soil microbial community displacement concerns raised by (Smagin *et al.*, 2022) ^[34] in soil management, yet neither community cites the other. The burst-release problem identified by (Ahmad *et al.*, 2023) ^[5] in fertiliser delivery and by (Baipaywad *et al.*, 2022) ^[9] in veterinary drug delivery represents the same engineering limitation in two sub-topics, but no paper in either domain references the other's characterisation of the problem.

Interpreting the Major Contradictions

The most substantive contradictions across the literature share a common root: they arise when aggregate review literature encounters dose-specific, formulation-specific, or context-specific empirical findings that its generalising framework cannot accommodate. The contradiction between (Rizwan *et al.*, 2021) ^[31] and (Costa *et al.*, 2022) ^[13] on hydrogel performance under salinity is not an irreconcilable empirical conflict it is a dose-by-formulation interaction that appears contradictory only because one source reports outcomes at 0.2% application rate and the other at 0.07%, without either constructing the dose-response curve that would reveal the relationship between them. Similarly, the contradiction between (Abdelghafar *et al.*, 2024) ^[2] and (Rajanna *et al.*, 2022) ^[29] on whether deficit or full irrigation maximises WUE is partly a consequence of optimising different objective functions water-use ratio versus absolute profitability rather than a genuine empirical disagreement about plant physiology. These contradictions are resolvable, but resolution requires experimental designs that current studies have not provided: factorial dose-by-environment experiments with pre-specified primary endpoints that permit direct

comparison across studies.

The contradiction between (Smagin *et al.*, 2022) ^[34] and the majority biodegradability literature whether rapid polymer degradation constitutes an environmental virtue or a performance failure is not resolvable by experiment because it is a design-objective conflict rather than an empirical dispute. Researchers designing for agronomic longevity and researchers designing for ecological compatibility are optimising genuinely incompatible targets, and the field requires an explicit framework that specifies acceptable biodegradation ranges by application context rather than treating degradability as a universal virtue or liability.

Shared Assumptions and Their Implications

Five foundational assumptions are shared across the literature with insufficient empirical scrutiny. The most consequential is the inference that laboratory-measured water retention translates directly to plant-available moisture under field ionic conditions an assumption falsified within the corpus itself by (Merino *et al.*, 2023) ^[26], who document a fivefold reduction in swelling between distilled and tap water, and by (Costa *et al.*, 2022) ^[13], who show that improved retention at the soil level can coincide with reduced plant biomass. The second is the equivalence of polymer biodegradation with environmental safety a logical non-sequitur demonstrated by the acknowledged generation of potentially toxic degradation products including acrylamide monomers and metal nanoparticles from materials whose bulk weight loss is presented as evidence of harmless mineralisation (Merino *et al.*, 2023; Somsesta *et al.*, 2024) ^[26, 35]. The third is the treatment of *in vitro* cytotoxicity screening against mammalian cell lines as sufficient evidence for agricultural ecosystem safety an assumption that conflates mammalian and ecological toxicology in a manner inconsistent with regulatory standards for pesticide and feed additive approval (Kumar *et al.*, 2022; Rajasekaran & Santra, 2015) ^[23, 30]. Together, these assumptions inflate the evidentiary status of available findings and create a systematic gap between what the literature claims and what it has demonstrated.

Future Directions

Four research priorities follow directly from this synthesis. Multi-season, multi-site replicated field trials with pre-registered primary endpoints represent the non-negotiable first step for every sub-topic: without field validation, the benefit-to-cost calculations, dose recommendations, and safety assessments that practitioners require cannot be derived from available evidence. Formulation-stratified experimental designs distinguishing synthetic polyacrylates, natural biopolymers, composite systems, and nanoparticle-loaded variants within the same study are necessary to replace category-level claims with the formulation-specific guidance that adoption decisions require. The resistance-selection dynamics of sustained-release delivery under repeated seasonal application demand collaborative investigation between polymer chemistry and evolutionary biology communities that have not yet engaged each other's literature. Finally, isotopically labelled degradation studies tracking polymer carbon and metal nanoparticles through soil profiles, plant tissue, and animal products over multi-year periods are prerequisite for the regulatory dossiers that commercial deployment of any hydrogel application will require. The field's theoretical foundations are substantively sound; its evidentiary base is not yet adequate to support the deployment claims its proponents routinely make.

Conclusion

This systematic review has evaluated the evidence base for hydrogel applications across soil management, crop productivity, pest control, and livestock nutrition and health. Across all four subtopics, hydrogels demonstrate consistent proof-of-concept functionality: they extend soil moisture retention, improve water use efficiency under moderate deficit conditions, enable sustained release of agrochemicals and nutrients beyond what conventional direct application achieves, and deliver antimicrobial and therapeutic compounds to livestock at reduced cytotoxic burden relative to unencapsulated agents. These findings are empirically robust within the conditions under which they were generated.

The central conclusion of this review is that the applied evidence base does not yet support deployment recommendations at commercial agricultural scale. Every positive outcome reported across the four subtopics was demonstrated under controlled laboratory or single-season greenhouse conditions. No multisite, multi-season replicated field trial exists for any hydrogel application in any sub-topic reviewed. The gap between proof-of-concept performance and field-validated efficacy is not a minor methodological limitation it is the defining constraint on the field's practical utility. Formulation-specific findings have been systematically overgeneralised to product categories, producing a review literature that conveys false consensus on the directionality and magnitude of hydrogel benefits. Specific formulations reduce water productivity, elevate soil salinity, decrease crop biomass, and fail to match conventional management outcomes under conditions directly relevant to their intended use.

The single most important research gap is the complete absence of multi-season field trial data across all four sub-topics. Resolving this gap is a prerequisite for every subsequent research priority economic analysis, regulatory approval, dose optimisation, and resistance monitoring none of which can be meaningfully conducted without field-scale performance data obtained under variable climate, soil heterogeneity, and commercial management conditions.

Hydrogels represent a genuinely versatile material platform whose crosslinking tunability, biodegradation programmability, and multi-payload capacity make them structurally suited to the simultaneous demands of water conservation, precision nutrient delivery, reduced pesticide loading, and antibiotic-free livestock management. Realising this potential requires the field to transition from materials characterisation to agronomic validation from demonstrating what hydrogels can do in optimal laboratory conditions to establishing what they deliver in the soils, climates, and farming systems where sustainable agriculture must be achieved.

Conflict of Interest

The authors declare no conflict of interest.

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