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Application of
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IN THIS ISSUE

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Contributors should keep notation, derivations, measurement conditions, and model assumptions explicit enough for later verification, comparison, and reuse in the scientific record.

ISSUE REGISTER

Document	Lead Author	Pages
Publication Record		i
Editorial Stewardship		ii
Issue Prospectus		vi
Hybrid Approach for Arsenic Remediation: Soil Washing Coupled with Hematite Nanoparticles in Cu-As-Au Mining Waste	Jameshourani et al.	1-6
Execution, Interaction, and Memory: A Coordination-First Ontology for Physics	Connelly	7-23
Quasi-Phase Matching Generation of the Anti-Stokes Component at Stimulated Raman Scattering	Kasumova	24-31
Foliar Application of Gehna Super Bio-stimulant Enhances Growth, Yield, and Nutrient Uptake in Maize (Zea mays L.) under South Indian Agroclimatic Conditions	Somashekar et al.	32-40
Action and Entropy: Base Physical Quantities	Morin	41-47
Research Index		48
Author Guidelines		50

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Hybrid Approach for Arsenic Remediation: Soil Washing Coupled with Hematite Nanoparticles in Cu-As-Au Mining Waste

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ABSTRACT

Copper–gold mining in the eastern Alps, Austria, has produced sulfide-rich tailings that continue to release arsenic (As) into the environment. This study examined the effectiveness of removing arsenic from mining waste using various chemical extractants, nanoparticle (NP) dosages, and different sample grain sizes. The goals are to extract arsenic and produce a concentrate for recovering valuable metals, such as copper and gold, through metallurgical processes. This paper presents an integrated experimental framework designed to simulate realistic remediation scenarios using hematite nanoparticles (HMNPs). Multiple extractants—ultrapure water (UPW), nitric acid (HNO₃), monosodium dihydrogen phosphate (NaH₂PO₄), and hydrogen peroxide (H₂O₂)—were used to explore arsenic mobilization under different chemical stress conditions. Among the tested extractants, 0.1 M HNO₃ showed the highest...

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FULL ABSTRACT

Copper–gold mining in the eastern Alps, Austria, has produced sulfide-rich tailings that continue to release arsenic (As) into the environment. This study examined the effectiveness of removing arsenic from mining waste using various chemical extractants, nanoparticle (NP) dosages, and different sample grain sizes. The goals are to extract arsenic and produce a concentrate for recovering valuable metals, such as copper and gold, through metallurgical processes. This paper presents an integrated experimental framework designed to simulate realistic remediation scenarios using hematite nanoparticles (HMNPs). Multiple extractants—ultrapure water (UPW), nitric acid (HNO₃), monosodium dihydrogen phosphate (NaH₂PO₄), and hydrogen peroxide (H₂O₂)—were used to explore arsenic mobilization under different chemical stress conditions. Among the tested extractants, 0.1 M HNO₃ showed the highest arsenic removal efficiency, significantly outperforming UPW, 0.1 M NaH₂PO₄, and 3% H₂O₂. The addition of NPs improved overall arsenic removal; however, the efficiency did not increase proportionally with higher NP concentrations. A concentration of 0.05 HNPs g/L resulted in slightly higher arsenic removal rates compared to 2.5 HNPs g/L and 5 HNPs g/L, likely due to particle aggregation at higher concentrations, which reduced the available reactive surface area. The texture of the mining waste also influenced removal efficiency. Finer particles promoted greater arsenic release under the H₂O₂ + HNP treatment, whereas coarser particles showed better responses to UPW and NaH₂PO₄. In contrast, HNO₃ consistently delivered high removal efficiencies across all particle sizes by directly dissolving the mineral compositions. The distinct oxyanion behavior of As underscores the necessity for strong extractants or NP-assisted approaches, as conventional methods optimized for cationic metals are less effective. Overall, HNO₃ proved to be the most effective single extractant, achieving removal efficiencies of up to 87.6% for As, 63.8% for Zn, 90.7% for Pb, and 85.97% for Cu. Post-treatment filtrates were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Instrumental Neutron Activation Analysis (INAA) to quantify As removal.

ARCHIVAL RECORD

RESEARCH ARTICLE

Hybrid Approach for Arsenic Remediation: Soil Washing Coupled with Hematite Nanoparticles in Cu-As-Au Mining Waste

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Abstract

Copper–gold mining in the eastern Alps, Austria, has produced sulfide-rich tailings that continue to release arsenic (As) into the environment. This study examined the effectiveness of removing arsenic from mining waste using various chemical extractants, nanoparticle (NP) dosages, and different sample grain sizes. The goals are to extract arsenic and produce a concentrate for recovering valuable metals, such as copper and gold, through metallurgical processes. This paper presents an integrated experimental framework designed to simulate realistic remediation scenarios using hematite nanoparticles (HMNPs). Multiple extractants—ultrapure water (UPW), nitric acid (HNO₃), monosodium dihydrogen phosphate (NaH₂PO₄), and hydrogen peroxide (H₂O₂)—were used to explore arsenic mobilization under different chemical stress conditions. Among the tested extractants, 0.1 M HNO₃ showed the highest arsenic removal efficiency, significantly outperforming UPW, 0.1 M NaH₂PO₄, and 3% H₂O₂. The addition of NPs improved overall arsenic removal; however, the efficiency did not increase proportionally with higher NP concentrations. A concentration of 0.05 HNPs g/L resulted in slightly higher arsenic removal rates compared to 2.5 HNPs g/L and 5 HNPs g/L, likely due to particle aggregation at higher concentrations, which reduced the available reactive surface area. The texture of the mining waste also influenced removal efficiency. Finer particles promoted greater arsenic release under the H₂O₂ + HNP treatment, whereas coarser particles showed better responses to UPW and NaH₂PO₄. In contrast, HNO₃ consistently delivered high removal efficiencies across all particle sizes by directly dissolving the mineral compositions. The distinct oxyanion behavior of As underscores the necessity for strong extractants or NP-assisted approaches, as conventional methods optimized for cationic metals are less effective. Overall, HNO₃ proved to be the most effective single extractant, achieving removal efficiencies of up to 87.6% for As, 63.8% for Zn, 90.7% for Pb, and 85.97% for Cu. Post-treatment filtrates were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Instrumental Neutron Activation Analysis (INAA) to quantify As removal.

Keywords: Arsenic removal, hematite nanoparticles, mining waste management, valuable metal extraction

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1 Introduction

The reprocessing of polymetallic low-grade ores previously considered economically unfeasible has gained renewed significance due to advances in extraction technologies and the increasing global demand for critical metals, such as copper, zinc, silver, and gold. Historically discarded materials, including tailings and mining residues, represent not only potential secondary metal resources but also persistent environmental hazards; due to the presence of sulfide minerals and associated potentially hazardous elements (PHEs), particularly arsenic [1]. These environmental risks are exacerbated by natural weathering processes that induce sulfide oxidation, resulting in acid mine drainage (AMD) and the subsequent mobilization of toxic elements into surrounding ecosystems [2].

This study examines the effectiveness of HMNPs (α -Fe₂O₃) combined with various chemical extractants to reduce arsenic bioavailability in legacy mining waste from the eastern Alps, Austria, an area historically affected by orogenic copper-gold mining activities. The main objectives are twofold: (1) to evaluate HMNPs' ability to adsorb and remove arsenic under different extraction conditions, and (2) to understand how soil particle size, mineralogical composition, and solution chemistry influence arsenic mobility and remediation success.

The significance of this research lies in addressing the dual challenge of environmental protection and sustainable resource recovery. Conventional mining waste remediation techniques often prove inadequate when dealing with the heterogeneity and chemical complexity of mine-contaminated substrates, emphasizing the need for adaptable and targeted approaches [3, 4]. Nanotechnology offers a promising alternative in this regard, with iron oxide-based nanomaterials demonstrating exceptional surface reactivity, tunable physicochemical properties, and relatively low toxicity, making them highly suitable for environmental remediation applications [5, 6].

Previous studies have explored a range of nanomaterials for arsenic remediation, including zero-valent iron, goethite, magnetite, and various carbon-based composites, highlighting their efficiency under specific environmental conditions [7, 8, 9]. Earlier works have demonstrated the potential of HMNPs to interact with a range of PHEs in complex mining waste matrix; however, their role in real-world remediation scenarios, particularly under field-representative extractant conditions, remains underexplored.

2 Role of Nanotechnology in Arsenic Remediation

Traditional methods for arsenic removal—such as physicochemical adsorption, redox reactions (both photochemical and chemical), and filtration—have shown limitations in efficiency and flexibility. The advent of nanotechnology has significantly advanced the remediation of arsenic from mining waste by enhancing removal methods and improving detection accuracy.

2.1 Nanoscale iron oxides

Iron oxide nanoparticles (IONPs) and iron nanoparticles (FeNPs) have been extensively studied for their high efficiency in removing pollutants, particularly arsenic, from contaminated soils and water. IONPs are especially effective due to their ability to bind arsenic through chemisorption, forming strong and stable chemical bonds with arsenic species. In contrast, carbon-based NPs typically rely on physisorption, which involves weaker, non-specific interactions; however, their adsorption performance can be significantly enhanced through surface modification.

Nanoscale iron oxides (nFeOs) demonstrate exceptional efficiency not only in removing arsenic but also in eliminating other toxic metals such as V, Cr, Co, Mn, Se, Mo, Cd, Pb, Sb, Tl, Th, and U. Their low toxicity, high reactivity, and resistance to desorption make them a promising material for environmental remediation. Among the various forms of iron oxides, goethite (α -FeOOH), hematite (α -Fe₂O₃), maghemite (γ -Fe₂O₃), and magnetite (Fe₃O₄) are recognized as the most efficient for such applications. The adsorption mechanism—whether chemisorption or physisorption—ultimately depends on the NP's composition and surface chemistry, which govern their interaction strength and selectivity toward contaminants.

Studies confirm that nFeOs efficiently remove arsenite AsO₃³⁻ and arsenate AsO₄³⁻ while minimizing secondary contamination risks. They also immobilize toxic metals in mining waste. Factors influencing the stability and transport of nFeOs include particle size, concentration, magnetism, solution chemistry, and environmental conditions [9].

NPs in concentrated solutions tend to aggregate due to increased collision rates, reducing stability compared to dilute solutions. For instance, smaller HMNPs exhibit higher aggregation rates due to surface property changes at reduced sizes [8]. Additionally, strong magnetic properties in IONPs contribute to increased aggregation. However, studies suggest that IONPs generally have low or negligible toxicity to living organisms [5].

2.2 Hematite nanoparticles

Hematite α -Fe₂O₃ is a stable, well-crystalline NP commonly found in mining waste and plays a key role in the iron biogeochemical cycle. Its high surface area, thermal stability, and abundant hydroxyl sites make it highly effective for adsorbing metalloids and trace metals [10]. Due to these properties, hematite is widely used in contaminant remediation, catalysis, gas sensing, and battery applications [11].

Studies have shown its ability to adsorb contaminants like copper, nickel, cobalt, cadmium, lead, zinc, and anions such as uranyl, phosphate, sulfate, and selenate. Common synthesis methods include precipitation, hydrothermal, and solvothermal techniques, which are valued for their simplicity and high yield. Preventing precursor coagulation is crucial for producing monodispersed HMNPs [12].

2.3 Factors influencing NP performance

The effectiveness of nanomaterials in arsenic remediation is governed by various environmental and operational factors. Among these, the pH and redox potential of mining waste are particularly important, as they significantly influence the chemical speciation and mobility of arsenic in mining waste. The presence of organic matter and the mineralogical composition of the mining waste also significantly affect how NPs interact within the mining waste matrix. Additionally, the specific surface area of IONPs is a key factor in optimizing their adsorption efficiency, as it determines the number of active sites available for binding arsenic. Particle size is vital to adsorption efficiency because it affects surface area, crystallinity, and site density. Hematite particles range from nanoscale to microns, with smaller sizes generally providing better adsorption due to increased surface reactivity [12].

2.4 Advantages of nanotechnology

Nanomaterials offer several advantages for arsenic remediation. Nanomaterials possess a high surface area that significantly increases their adsorption or catalytic activity. This structural feature also contributes to improved detection capabilities and greater selectivity, allowing for lower detection limits and increased accuracy in identifying arsenic presence.

In the context of mining waste reclamation, various nanomaterials have proven effective. These include zeolites, IONPs, phosphate-based NPs, and carbon nanotubes. Among them, zero-valent iron (nZVI) and IONPs have been the most extensively studied due to their strong chemical affinity for arsenic and their effectiveness across a wide range of mining waste types [5, 6]. IONPs tend to aggregate based on concentration and pH. Brownian motion increases collisions, leading to aggregation, especially at concentrations above 50 mg/L [13].

3 Chemical and mineralogical composition of the mine waste

Table 1. Selected components and particle sizes of the mining waste

Sample Name	Particle size (mm)	As (ppm)	Au (ppb)	Ag (ppm)	Cu (ppm)	Mn (ppm)	Mg (%)
WBa ^a _12	0.18–2	570	81	0.14	252	895	0.77
WB_12	< 0.18	3180	792	0.72	983	1210	1.45
WBb ^b _13	0.18–2	3450	415	0.26	440	1700	0.55
WB_13	< 0.18	5920	858	1.51	1780	1730	0.91

^aWeißenbach12 (WB) 1.5 m depth from surface; ^bWeißenbach13 (WB) 2.5 m depth from surface

The tailings waste contains primary minerals like chalcopyrite (CuFeS_2), bornite (Cu_5FeS_4), and covellite (CuS), which were part of the original ore. Secondary minerals formed through weathering and oxidation include malachite ($\text{Cu}_2\text{CO}_3(\text{OH})_2$), azurite ($\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$), cuprite (Cu_2O), and brochantite ($\text{Cu}_4\text{SO}_4(\text{OH})_6$). These minerals show the transformation of sulfides into oxides, carbonates, and sulfates over time. Various techniques have been developed to treat mining waste, primarily focusing on containing or immobilizing pollutants or on cleaning up and removing them. Each case is different, so methods need to be tailored or combined. However, many remediation options face significant challenges [3, 14].

The mineral composition of historical tailing waste significantly affects arsenic (As) removal efficiency. Iron oxides (e.g., hematite, goethite, magnetite) are the primary arsenic adsorbents, while quartz is inert and does not contribute to removal. Clay minerals moderately aid adsorption, carbonates help stabilize arsenic through precipitation, and sulfides can release arsenic, requiring pre-treatment.

Magnesium minerals enhance stability but may compete with iron for binding, while phosphates reduce arsenic removal by competing for adsorption sites. Silicates (e.g., feldspar, mica) have minimal impact. Understanding these minerals is crucial for effective arsenic remediation strategies [15, 16, 17]. The chemical composition of the samples before treatment is presented in Table 1, which also indicates the presence of precious and base metals, as well as some hazardous elements such as arsenic.

4 Material and Methods

4.1 Sample collection and preparation

Samples containing sulfide-rich tailings were obtained from one mine waste dump at two different depths (Weißenbach12: 1.5 m and Weißenbach13: 2.5 m). The samples were air-dried and sieved to < 0.18 mm and 0.18 – 2 mm for general characterization and arsenic removal.

4.2 Reagents and pH conditions for removal of arsenic

A 0.1 M phosphate solution prepared from salts such as NaH_2PO_4 was used to facilitate the displacement of arsenate ions from grain size particles, operating effectively at a pH of 6.1. Additionally, 3% hydrogen peroxide (H_2O_2) was employed to oxidize sulfide minerals, promoting the release of arsenic and associated metals into the aqueous phase at a pH of approximately 6.5. UPW served as a blank solution and was also utilized to assess the influence of HMNPs under near-neutral conditions (pH 6–7). Furthermore, concentrated nitric acid (0.1 M HNO_3), a strong oxidizing agent, was applied under highly acidic conditions (pH 1) to ensure the complete oxidation and dissolution of mineral constituents.

4.3 Hematite nanoparticles

HMNPs ($\alpha\text{-Fe}_2\text{O}_3$; 20 – 50 nm; 99.8% purity) were utilized to evaluate their impact on the removal of potentially harmful elements (PHEs) in mining waste. Stock suspensions of HMNPs were prepared at concentrations of 5.0 g/L, 2.5 g/L, and 0.05 g/L using various extractants: UPW, 0.1 M nitric acid (HNO_3), 0.1 M monosodium dihydrogen phosphate (NaH_2PO_4), and 3% hydrogen peroxide (H_2O_2). To prevent NP aggregation, 5 mM sodium citrate was added as a stabilizing agent. The suspensions were stirred for 30 minutes and subsequently sonicated for 15 minutes before soil application.

Samples were introduced into the NP suspensions, and the mixtures were agitated on a rotary shaker at 13 rpm for periods of 5 days and 10 days in the dark. The pH of the solutions was adjusted to between 6.0 and 7.2 using 0.1 M HCl or NaOH except for the HNO_3 -based suspensions, which maintained an acidic pH of ~ 1. For the H_2O_2 treatment, 10 g of sample was mixed with 100 ml of 3% hydrogen peroxide and stirred at 77°C and 240 rpm for 2 hours to promote oxidation of sulfide minerals. Subsequently, 0.5 g of HMNPs was added, and the mixture was stirred at 40°C for 24 hours, with pH adjusted to 6.5. Parallel control experiments were conducted under identical conditions but without the addition of NPs.

4.4 Mining waste treatment and metal extraction

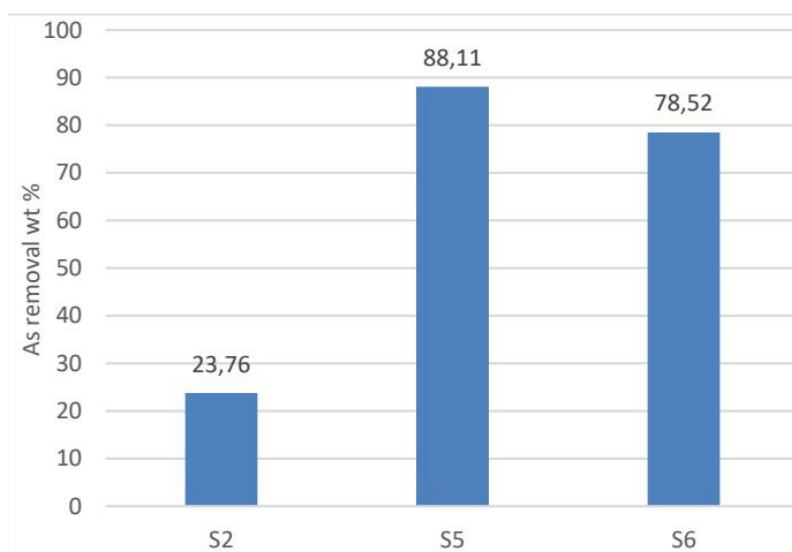
For each treatment, 5 g or 10 g of sample was combined with 50 mL or 100 mL of NP suspension and control solution in polypropylene containers (ratio is 1:10). The mixtures were homogenized by shaking for 5 days and 10 days under dark conditions. After treatment, samples were centrifuged at 2400 rpm for 10 minutes, and the supernatants were filtered through 0.45 μm membrane filters. The filtered extracts were then analyzed to determine the concentration of bioavailable PHEs and removal efficiency. The treated samples were dried at room temperature and stored for further analysis by INAA following 4-acid digestion and ICP-MS [6, 18].

5 Results and Conclusions

The study demonstrated that arsenic (As) removal efficiency is heavily dependent on the type of extract, NP dosage, and grain particle size. Among the tested extractants, HNO_3 delivered the highest As removal efficiency, performing significantly better than UPW, NaH_2PO_4 , and H_2O_2 . However, H_2O_2 had a much shorter reaction time (1 hour) compared to the other methods (5 and 10 days), but still produced promising results, especially with NPs, and could be further optimized for improved performance.

Table 2. Conditions and descriptions of the suspensions

Symbol	Condition and Description
S1	UPW, sample of 0.18–2 mm, 5 HNPs g/L
S2	UPW, sample of 0.18–2 mm without NPS
S3	NaH ₂ PO ₄ , sample of 0.18–2 mm, 5 HNPs g/L
S4	NaH ₂ PO ₄ sample of 0.18–2 mm without NPS
S5	HNO ₃ sample of 0.18–2 mm, 5 HNPs g/L
S6	HNO ₃ sample of 0.18–2 mm without NPS
S7	UPW, sample of 0.18–2 mm, 0.05 HNPs g/L
S8	UPW, sample of 0.18–2 mm, 2.5 HNPs g/L
S9	UPW, sample of 0.18–2 mm, 5 HNPs g/L
S10	H ₂ O ₂ with 5 HNPs g/L, sample of < 0.18 mm
S11	H ₂ O ₂ with 5 HNPs g/L, sample of 0.18–2 mm

**Figure 1.** The As removal [wt.%] of the blank suspension vs. the HNO₃ with HNPs and without HNPs

The addition of NPs generally enhanced As removal; however, increasing the mass fraction of NPs does not always result in a proportional increase in contaminant removal. Higher nominal NP loading (5 HNP g/L) can underperform because the extra mass no longer translates into available active surface due to aggregation, passivation, mass-transfer limits, or changes in solution chemistry—or because of experimental artifacts.

Particle size of samples also influenced performance: for H₂O₂ + NPs, finer particles (< 0.18 mm) improved As removal, because more reactive surface area and coatings were available for oxidation and release. For UPW and NaH₂PO₄, which are weak extractants, coarser particles (0.18 – 2 mm) were more effective because As was more weakly bound and could leach, whereas finer particles held As too strongly for pure water to remove. Strong extractants like HNO₃ dissolve the mineral composition and release As regardless of grain size. Finer particles may still give slightly higher efficiency (more surface area, faster dissolution), but the difference is less pronounced because HNO₃ is powerful enough to attack both coarse and fine fractions. Furthermore, deeper layers (up to 2.5 m depth) contained higher concentrations of hazardous elements as well as Au, Cu, and Ag.

Chemically, arsenic behaves differently from heavy metals due to its oxyanion nature, which makes it harder to remove with methods designed for cationic metals. Thus, if NPs are not used, a strong extract such as HNO₃ is necessary to achieve effective As removal (pH ~ 1). Importantly, the extractant that works best for As may not be the most efficient for other hazardous metals. However, the HNO₃ could remove 63.8% of the Zn, 87.6% of As, 85.97% of the Cu, and 90.7% of Pb. Comparison of the removal efficiency of As with the blank solution, with the HNO₃ solution, and the removal efficiency of different extractants on As removal is shown in Figures 1 and 2.

The efficiency of combining chemical extraction with HMNPs for arsenic removal depends on the mineralogical and chemical properties of the mining waste. Nitric acid (HNO₃) proved to be the most effective extractant, achieving up to 87.6% arsenic removal, while also extracting copper (Cu), zinc (Zn), and lead (Pb) in parallel. In cases where the mineralogical and chemical characteristics of the mining waste are compatible with the NPs, these NPs can be partly reused through selective extraction methods, improving cost efficiency and sustainability.

After As removal, both the filtrate and the solid leach residue will be further treated to recover as many different valuables as possible. From the filtrate, copper could be separated from arsenic, for example, by means of cementation, while the solid concentrate or leach residue could be treated using different approaches depending on the amount of valuable elements present. Low-Cu material could be leached with cyanide to obtain Au, whereas Cu-rich material could be treated following pyro- or hydrometallurgical standard procedures, where Au will be enriched in a potential anode slime. Ultimately, the extraction of As is an important part of treating these historical mine wastes; however, As is only one of the many components in focus.

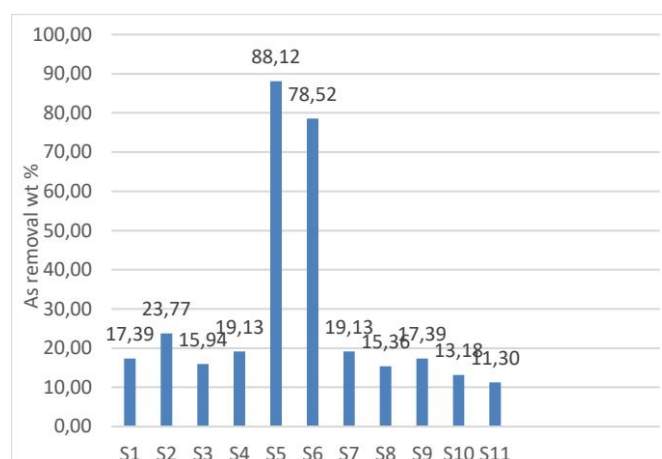


Figure 2. The As removal [wt.%] of different extractants under different conditions

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Execution, Interaction, and Memory: A Coordination-First Ontology for Physics

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ABSTRACT

Modern physics successfully models dynamical evolution once a state description is given but lacks a minimal ontology explaining why irreversible temporal structure, classicality, and large-scale cosmological phenomena emerge at all. This monograph proposes a coordination-first framework in which reality is generated by three modal operations—Execution (E), Interaction (I), and Memory (M)—acting on a dynamically evolving coordination graph. The framework draws upon and extends insights from process philosophy, category theory, and network science, positioning the physics of coordination as a bridge between natural science and the humanities. Part I develops the core formalism: the EIM algebra, emergent geometry, coordination field equations, and cosmological consequences, together with empirical predictions. Part II extends the framework to resolve major paradoxes across physics, cosmology, mathematics, and philosophy—from the measurement problem and black hole information loss to Gödel's incompleteness theorems and the hard problem of consciousness—while revealing unexpected structural connections between seemingly unrelated domains. Part III charts prospective applications and empirical frontiers, identifying near-term testable predictions in astrophysics, biological percolation, economic coordination, and quantum technology that leverage emerging 2026–2030 datasets and experimental capabilities. The monograph concludes by examining societal implications of coordination ontology for artificial intelligence ethics, climate governance, and the philosophy of collective action.

Index Terms: coordination ontology • arrow of time • quantum measurement • emergent spacetime • dark sector • percolation threshold • process philosophy • paradox resolution • Hubble tension • biological phase separation

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Abstract

Modern physics successfully models dynamical evolution once a state description is given but lacks a minimal ontology explaining why irreversible temporal structure, classicality, and large-scale cosmological phenomena emerge at all. This monograph proposes a coordination-first framework in which reality is generated by three modal operations—Execution (E), Interaction (I), and Memory (M)—acting on a dynamically evolving coordination graph. The framework draws upon and extends insights from process philosophy, category theory, and network science, positioning the physics of coordination as a bridge between natural science and the humanities. Part I develops the core formalism: the EIM algebra, emergent geometry, coordination field equations, and cosmological consequences, together with empirical predictions. Part II extends the framework to resolve major paradoxes across physics, cosmology, mathematics, and philosophy—from the measurement problem and black hole information loss to Gödel's incompleteness theorems and the hard problem of consciousness—while revealing unexpected structural connections between seemingly unrelated domains. Part III charts prospective applications and empirical frontiers, identifying near-term testable predictions in astrophysics, biological percolation, economic coordination, and quantum technology that leverage emerging 2026–2030 datasets and experimental capabilities. The monograph concludes by examining societal implications of coordination ontology for artificial intelligence ethics, climate governance, and the philosophy of collective action.

Keywords: *coordination ontology, arrow of time, quantum measurement, emergent spacetime, dark sector, percolation threshold, process philosophy, paradox resolution, Hubble tension, biological phase separation, economic fragility, topological quantum computing, AI ethics, climate governance, collective action*

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1 Introduction

Contemporary physical theories describe the evolution of systems within spacetime but typically assume spacetime itself as a primitive, pre-given structure. General relativity models the dynamical geometry of spacetime but presupposes a differentiable manifold; quantum mechanics specifies unitary evolution on a Hilbert space but leaves the transition to definite measurement outcomes unexplained; thermodynamics introduces an arrow of time through the second law but does not derive temporal asymmetry from first principles. This collection of frameworks, despite extraordinary empirical success, rests on what we term a “snapshot ontology” — a view of physical reality as a sequence of instantaneous state descriptions connected by dynamical laws (Albert, 2000; Maudlin, 2007).

The snapshot ontology captures relations among co-existing entities at a given time but does not explicitly incorporate the procedural accumulation of irreversible history. Yet several of the deepest puzzles in modern physics — thermodynamic irreversibility, quantum measurement, and cosmological structure formation — depend on the progressive stabilization of physical states. Each involves the idea that something becomes settled in a way that cannot be undone: entropy increases, measurement outcomes become definite, and cosmic structures crystallize out of an initially homogeneous background. These observations suggest that the accumulation of irreversible constraint may be ontologically prior to the geometric structures used to describe them.

The parallel to human experience is immediate and instructive. In social life, coordination precedes structure: a market emerges from trade, a legal system from adjudication, a language from communicative interaction. No social institution exists as a snapshot; each is the product of accumulated, irreversible coordination history. The sociological insight that “structure is the trace of process” (Giddens, 1984) finds a striking resonance in the physics proposed here. If physical reality is likewise a coordination process rather than a static configuration, then the deep structural similarities between physics and social science may reflect a shared ontological foundation rather than a mere metaphor.

Process philosophy, particularly in the traditions of Whitehead (1929) and more recently Stengers (2011), has long argued that becoming is more fundamental than being. Whitehead's “actual occasions” — events that achieve determinacy through a process of “concrescence” — bear a strong family resemblance to the coordination events of the present framework. Category-theoretic approaches to physics (Baez & Stay, 2011;

Coecke & Kissinger, 2017) have formalized some of these intuitions by treating processes, rather than objects, as the fundamental morphisms of physical theory. Meanwhile, the emergence of spacetime from entanglement structure in holographic settings (Maldacena, 1999; Van Raamsdonk, 2010; Cao & Carroll, 2018) and the development of causal-set theory (Bombelli et al., 1987; Surya, 2019) have opened the door to frameworks in which spacetime geometry is derivative rather than fundamental.

Network science provides a further bridge. The study of percolation on complex networks (Newman, 2018; Barabási, 2016) has revealed universal phase-transition behavior governing the emergence of large-scale connectivity from local interactions — precisely the kind of mechanism the present framework invokes for the quantum-to-classical transition, structure formation, and the emergence of spacetime itself. The mathematical tools of percolation theory, originally developed for materials science and later applied to epidemiology, social networks, and information cascades, turn out to be naturally suited to a coordination-first ontology of physics.

This monograph develops a minimal procedural ontology in which the universe is fundamentally a coordination process rather than a configuration of particles or fields. We introduce three modal operations — Execution, Interaction, and Memory — and show that their algebraic structure generates temporal irreversibility, governs the quantum-to-classical transition, and produces effective gravitational dynamics. Part I presents the core formalism. Part II resolves a wide range of paradoxes across physics, cosmology, mathematics, and philosophy. Part II charts prospective applications and identifies near-term empirical tests that could validate or falsify the framework, while also examining the societal and humanistic implications of a coordination-first worldview.

2 The EIM Ontology

2.1 Primitive Operations

All physical processes are described by three modal operations:

Execution (E): the actualization of physical events. Execution transforms potential states into realized occurrences. Unlike standard Hamiltonian evolution, execution is not assumed to be reversible or unitary; its character depends on the coordination regime in which it operates. A useful social analogy is the act of decision-making: a firm executes a strategic choice, transforming a space of possibilities into a definite commitment. In physics, execution is the moment at which something happens — a particle decays, a photon is emitted, a quantum of energy is exchanged.

Interaction (I): finite-speed coordination between events. Interaction propagates the consequences of execution across the coordination graph, subject to a fundamental speed bound. This operation encodes the causal structure that, in the high-coordination limit, manifests as light-cone structure and Lorentz invariance. Socially, interaction corresponds to communication: the propagation of information, influence, or constraint between agents. Just as a message takes time to travel between sender and receiver, physical interaction propagates at finite speed across the coordination graph.

Memory (M): irreversible stabilization of outcomes. Memory locks the results of interaction into a permanent constraint record. This irreversibility is not a statistical approximation but a structural feature of the ontology (cf. Prigogine, 1980; Smolin, 2013). In social terms, memory is the institution: the law that has been enacted, the contract that has been signed, the precedent that constrains future action. Once memory-locked, a coordination outcome becomes part of the permanent record that shapes all subsequent coordination.

Let the evolving coordination structure be represented by a dynamic graph

$$G(t) = (V(t), E(t))$$

where $V(t)$ is the vertex set of realized events and $E(t)$ is the edge set of established interactions. The accumulated irreversible constraint is denoted

$$C_M(t).$$

2.2 Irreversibility as Structural Non-Commutativity

The defining structural feature of the EIM ontology is a non-commutativity relation between Interaction and Memory:

$$IM = MI + \Delta C_M, \quad \Delta C_M > 0$$

This relation states that interacting before memory-locking produces a different — and irreversibly richer — coordination state than memory-locking before interacting. The monotonicity condition follows immediately:

$$dC_M/dt > 0.$$

Temporal direction arises from monotonic constraint accumulation rather than from boundary conditions imposed on time-symmetric laws. This distinguishes the EIM framework from the Past Hypothesis approach (Albert, 2000) and from decoherence-based accounts (Zurek, 2003). The arrow of time is a theorem of the algebraic structure, not an axiom about initial conditions.

The non-commutativity relation (3) can be compared to the canonical commutation relation $[x, p] = i\hbar$ in quantum mechanics, but with a crucial difference: the EIM commutator is real and positive, generating irreversible constraint growth rather than unitary evolution. Where the Heisenberg commutator generates the uncertainty principle, the EIM commutator generates the irreversibility principle. This structural parallel suggests that quantum mechanics and thermodynamics may be two aspects of a single algebraic structure — a unification that has long been sought but never achieved within the snapshot ontology.

The sociological parallel is again instructive. In institutional economics, the order in which agreements are reached matters irreversibly: a contract negotiated before a regulatory change produces a different institutional landscape than one negotiated after. This path-dependence is not a

contingent feature of social life but a structural consequence of the non-commutativity of coordination operations — the same non-commutativity that, in the EIM framework, generates the arrow of time in physics.

2.3 Relation to process Philosophy and Category theory

The EIM ontology shares motivations with Whitehead's process philosophy (Whitehead, 1929) and category-theoretic approaches to physics (Baez & Dolan, 1995; Coecke & Kissinger, 2017). Whitehead's "actual occasions" undergo a process of concrescence — a coming-together of influences into a definite, unified experience — that closely parallels the EIM sequence of execution, interaction, and memory-locking. The key difference is specificity: where Whitehead's metaphysics remains largely qualitative, the EIM framework specifies three concrete operations with a definite algebraic relation, providing a concrete and mathematically tractable realization of process-relational metaphysics.

Category theory provides the natural mathematical language for this enterprise. In a monoidal category, the composition of morphisms (processes) is the fundamental operation, and objects (states) are defined by their role in compositions rather than by intrinsic properties. The EIM operations can be formalized as morphisms in a coordination category, with the non-commutativity relation (3) encoding a non-trivial braiding structure. This formalization connects the EIM framework to the broader program of categorical quantum mechanics (Abramsky & Coecke, 2004) and opens the door to rigorous mathematical development.

3 Coordination Density and Emergent Geometry

3.1 Coordination Density

Define the coordination density

$$\phi = dC/d\Omega$$

where C is the total coordination constraint and $d\Omega$ is a graph volume element measuring the "size" of each region of the graph proportional to the number of vertices and edges it contains. Coordination density is the fundamental local variable of the theory, playing a role analogous to energy density in general relativity or order parameter in Landau theory. It measures how densely coordinated a region of the graph is — how much irreversible history has been accumulated per unit of graph volume.

The concept of coordination density has natural analogues in the social sciences. In urban geography, population density and economic activity density determine the character of a neighborhood; in network science, node degree and clustering coefficient measure the intensity of local connectivity. The EIM framework proposes that a formally analogous quantity governs the character of physical reality itself, determining whether a region exhibits quantum, transitional, or classical behavior.

3.2 Metric as Derivative

The metric tensor arises as a derivative relation between execution frequency and coordination constraint:

$$g_{\mu\nu} = d\omega/dC$$

where ω denotes execution frequency. The metric summarizes the relationship between the rate of physical happening and the accumulated coordination history. Regions with high accumulated constraint (dense memory) have lower effective execution frequency — time runs slower — while regions with low accumulated constraint have higher execution frequency. This provides an intuitive coordination-theoretic origin for gravitational time dilation: clocks run slower in deep gravitational wells because those regions have accumulated more coordination history.

The total coordination state is:

$$C = \int g_{\mu\nu} d\omega + C_M.$$

Standard general relativity retains only the geometric derivative and discards the integral memory contribution C_M — an approximation that works in the high-coordination regime but leads to systematic errors at cosmological scales. This omission is analogous to an economist modeling market dynamics using only instantaneous supply and demand curves while ignoring the accumulated institutional history (contracts, regulations, precedents) that constrains future market behavior.

3.3 Connection to Holographic and Entropic Gravity

The framework resonates with holographic principles (Bousso, 2002; Maldacena & Susskind, 2013) and entropic gravity (Verlinde, 2011, 2017; Jacobson, 1995) but identifies the primitive substrate as the concrete process of irreversible coordination rather than entanglement or entropy in the abstract. The Bekenstein-Hawking entropy formula, which relates the entropy of a black hole to its horizon area, acquires a direct coordination-theoretic interpretation: the area measures the total accumulated coordination constraint on the boundary. The holographic principle — that the physics of a region is encoded on its boundary — becomes the statement that the coordination history of a volume is fully determined by the coordination state of its boundary, a natural consequence of the finite-speed interaction postulate.

4 Field Equations of Coordination

4.1 Coordination Dynamics

The evolution of coordination density obeys a reaction-diffusion equation:

$$\partial_t \phi = D \nabla^2 \phi + S(\rho, \phi) - \lambda \phi$$

Each term has a clear physical and social interpretation:

$D\nabla^2\Phi$: Coordination diffusion, governing spatial spread via interaction at finite speed. This term captures the tendency of coordination to spread from densely coordinated regions to sparsely coordinated ones — analogous to the diffusion of information, technology, or institutional practices across social networks.

$S(\rho, \phi)$: Execution-driven coordination source, depending on local matter-energy density p and existing coordination density. This term represents the generation of new coordination through physical events — the “source” of coordination history. In social terms, it corresponds to the creation of new agreements, transactions, or communications that add to the institutional record.

$\lambda\Phi$: Memory-locking rate, representing irreversible transfer from the dynamical field to accumulated constraint C_M . This term captures the progressive stabilization of coordination outcomes — the rate at which fluid, reversible coordination becomes permanently locked. In economic terms, it corresponds to the rate at which market transactions become settled, contracts become enforceable, and prices become committed.

The reaction-diffusion structure of equation (8) is significant because it places the coordination field equation in a well-studied mathematical class with known phase-transition behavior, stability properties, and pattern-formation dynamics (Cross & Hohenberg, 1993). This mathematical kinship is not accidental: the EIM framework proposes that the same coordination dynamics that govern pattern formation in chemical and biological systems also govern the emergence of spacetime structure and the quantum-to-classical transition.

4.2 The Percolation Threshold

A percolation threshold ϕ_c (Stauffer & Aharony, 1994; Grimmett, 1999) separates qualitatively distinct coordination regimes:

Regime	Physical Behavior
$\phi < \phi_c$	Quantum-dominant: superposition, entanglement, probabilistic outcomes
$\phi \approx \phi_c$	Decoherence transition: progressive classicalization
$\phi \gg \phi_c$	Classical-relativistic: deterministic evolution, smooth spacetime

The percolation threshold is a concept borrowed from network science and statistical physics, where it denotes the critical connectivity at which a network develops a “giant component” — a connected subgraph spanning the entire system. Below the threshold, the network consists of disconnected clusters; above it, a single connected component dominates. In the EIM framework, this phase transition governs the quantum-to-classical boundary: below ϕ_c coordination is fragmented and outcomes are probabilistic; above ϕ_c , coordination percolates into a coherent, classical record.

The social analogue is equally illuminating. In sociology, the percolation threshold has been invoked to explain the emergence of collective behavior from individual interactions: a protest movement “percolates” when enough local connections form to create a society-wide movement (Granovetter, 1978; Watts, 2002). The EIM framework proposes that the same mathematical structure governs the emergence of classical reality from quantum interactions.

4.3 Classical Limit

In the high-coordination limit, constraint gradients act as effective curvature sources:

$$\nabla^2 C_M \sim R_{\mu\nu}$$

recovering the Einstein field equations as a macroscopic approximation (cf. Jacobson, 1995; Padmanabhan, 2010). General relativity, in this view, is the “thermodynamics” of the coordination field — a macroscopic effective theory that captures the average behavior of coordination dynamics in the high-density limit while neglecting fluctuations and memory effects that become important at cosmological and quantum scales.

4.4 Quantum Limit

Below threshold, incomplete memory-locking produces probabilistic outcomes:

$$P_i \propto \exp(-\Delta C_M / \hbar)$$

providing an intrinsic origin for the Born rule without observer-dependent collapse. Outcomes with higher coordination cost (larger ΔC_M) are exponentially suppressed, while outcomes with lower coordination cost are exponentially favored. This is not a postulate but a consequence of the non-commutative algebraic structure: the probability of an outcome is determined by the cost of memory-locking it into the coordination record.

5 Cosmological Consequences

5.1 Dark Sector Reinterpretation

The neglected accumulated constraint C_M produces effective gravitational sources reinterpreting dark-sector phenomena (Planck Collaboration, 2020):

Local constraint gradients produce dark-matter-like effects, generating additional gravitational attraction beyond visible matter — mechanistically distinct from MOND (Milgrom, 1983) and from particle dark matter models. The coordination interpretation predicts that dark-matter-like effects should be environment-dependent — stronger in regions with steeper coordination gradients — a prediction that distinguishes it from both MOND and cold dark matter.

Global constraint accumulation produces dark-energy-like expansion pressure, providing a dynamical mechanism for cosmic acceleration. As the universe's total accumulated constraint C_M grows monotonically, it generates an effective repulsive contribution to the cosmic expansion equation that mimics a cosmological constant but is dynamical rather than static.

Vacuum-energy suppression: The coordination framework provides a natural resolution of the cosmological constant problem — the notorious 120-order-of-magnitude discrepancy between the quantum field theory prediction and the observed vacuum energy:

$$\rho_M = \rho_{\text{Planck}} \cdot \exp(-\phi_{\text{Planck}}/\phi_0)$$

The exponential suppression arises because the vast coordination density at the Planck scale ϕ_{Planck} exponentially dilutes the effective vacuum energy through memory-locking, reducing it to the observed value without fine-tuning (cf. Kaloper & Padilla, 2014).

5.2 Structure Formation

Percolation theory predicts scale-dependent structure formation governed by coordination connectivity thresholds, with scale-invariant clustering near criticality (Sylos Labini et al., 1998). The cosmic web — the filamentary large-scale structure of the universe — is, in this view, the visible trace of the coordination graph's percolation structure. Filaments are high- ϕ coordination corridors; voids are low- ϕ regions where coordination has not percolated. The statistical properties of this structure (power spectra, void size distributions, filament lengths) are determined by the universality class of the underlying percolation transition and can be compared with predictions from standard Λ CDM cosmology.

6 Empirical Predictions and Falsifiability

The EIM framework generates specific, quantitative predictions distinguishable from standard physics:

Prediction 1: Environmental variation in effective acceleration scales near percolation boundaries. The gravitational acceleration in galactic outskirts should depend on the local coordination environment — void vs. filament — producing systematic variations in galaxy rotation curves that correlate with large-scale structure.

Prediction 2: Structure-formation anomalies correlated with large-scale coordination density. The abundance and maturity of galaxies at high redshift should exceed Λ CDM predictions in regions of early coordination percolation, consistent with recent JWST observations of unexpectedly massive early galaxies.

Prediction 3: Non-Markovian gravitational memory effects in merging-cluster systems. Galaxy cluster mergers should exhibit gravitational residuals — deviations from the predictions of standard gravity — that depend on the merger history (accumulated C_M) rather than just the current mass distribution. These residuals are analogous to the hysteresis observed in magnetic materials and should be detectable in precision weak-lensing studies of merging clusters.

Prediction 4: Scale-dependent birefringence associated with historical constraint accumulation. Photons traversing regions with different coordination histories should experience slightly different effective refractive indices, producing a polarization-dependent propagation effect detectable in CMB polarization data or precision pulsar timing.

Falsifiability: Detection of strictly environment-independent gravitational parameters at high precision — confirming that G , H_0 , and S_8 are truly universal constants with no environmental variation — would falsify the coordination-dependent predictions of the EIM framework. Similarly, confirmation that the quantum-to-classical transition depends only on system size (as in standard decoherence theory) and not on coordination connectivity would falsify the percolation model of classicalization.

7 Philosophical Implications

Arrow of time. The arrow of time is a structural consequence of non-commutative modal operations, not a boundary condition on time-symmetric laws (cf. Price, 1996; Smolin, 2013). This resolution is philosophically significant because it makes temporal asymmetry intrinsic to the ontology rather than contingent on cosmological initial conditions — a position that aligns with the phenomenological observation that time's passage is experienced as fundamental rather than derivative.

Measurement problem. The quantum-to-classical transition is a coordination percolation phenomenon requiring no observers, consciousness, or many-worlds branching (cf. Zurek, 2003; Schlosshauer, 2007). This dissolves the measurement problem by replacing the ill-defined notion of "observation" with a well-defined physical process: the crossing of a percolation threshold in the coordination graph. The philosophical implications extend to epistemology: knowledge itself can be understood as the stabilization of coordination in cognitive systems that mirrors the physical process of memory-locking.

Spacetime ontology. Spacetime is an emergent record of coordination history, compatible with the quantum gravity research consensus that spacetime is not fundamental (Huggett & Wüthrich, 2013; Crowther, 2016). The philosophical implication is a form of structural realism in which the structure that is "real" is the coordination graph rather than the spacetime manifold — a position with important consequences for debates about the ontology of space, time, and physical law.

Physical law. Laws are regime-dependent approximations to coordination dynamics, with antecedents in effective field theory (Cao & Schweber, 1993) and Cartwright's (1999) critique of universality. Physical laws, in this view, are not eternal Platonic truths but emergent regularities that hold within specific coordination regimes — a position with implications for the philosophy of science and the debate between realism and anti-realism about scientific laws.

8 Part II

8.1 Resolving Paradoxes and Coordinating Disparate Phenomena

Many apparent paradoxes in physics, mathematics, and philosophy arise from treating reality as particulate or snapshot-based, ignoring the procedural, non-Markovian history that the coordination-first framework places at the center of ontology. By prioritizing coordination as the primitive, the EIM framework dissolves these tensions structurally. Moreover, the paradox resolutions reveal deep connections between physics and the human sciences: the same coordination dynamics that resolve quantum measurement paradoxes illuminate decision-making in sociology, the same percolation structures that explain black hole information loss clarify institutional path-dependence in political science, and the same non-commutativity that generates the arrow of time underlies the irreversibility of historical events.

9 Quantum Paradoxes

Quantum paradoxes stem from particulate, observer-dependent interpretations that treat measurement as an exogenous intervention rather than an endogenous coordination process. The coordination-first framework redefines quantum systems as regions of incomplete coordination — unfinished coordination events — resolving these paradoxes without hidden variables, many-worlds branching, or observer-dependent collapse.

9.1 The Measurement Problem

Standard issue. Why does observation “collapse” a superposition into a definite outcome? The measurement problem has plagued quantum mechanics since its inception (von Neumann, 1955; Bell, 1987), generating a proliferation of interpretations — Copenhagen, many-worlds, Bohmian mechanics, spontaneous collapse — none of which commands consensus.

Coordination resolution. Measurement is percolation completion. A quantum system in a subcritical regime ($\phi < \phi_c$) transitions to a definite outcome when execution drives ϕ across ϕ_c , integrating the event into the macroscopic coordination record. No observer is needed — the transition is a phase transition in the coordination graph, as impersonal and observer-independent as the freezing of water.

Outcome probabilities follow equation (10), deriving the Born rule intrinsically: higher-cost coordination paths are exponentially suppressed, lower-cost paths exponentially favored. The Born rule, which in standard quantum mechanics is an additional postulate, emerges here as a theorem of the algebraic structure.

Interdisciplinary connection. The measurement-as-percolation model has a direct parallel in the sociology of decision-making. In organizational theory, decisions remain “superposed” (unresolved, with multiple options alive) until sufficient coordination among stakeholders crosses a threshold and the decision “percolates” into institutional reality (March & Olsen, 1989). Legal proceedings exhibit the same structure: evidence remains potential until coordinated and recorded in procedural history, at which point it becomes part of the permanent record — memory-locked. The EIM framework suggests that this parallel is not metaphorical but structural: social and physical measurement share the same coordination dynamics.

9.2 Entanglement and the epr Paradox

Standard issue. Measurement correlations between spatially separated entangled particles appear to violate locality, challenging the completeness of quantum mechanics (Einstein et al., 1935; Bell, 1964).

Entanglement is pre-coordinated topology. Entangled particles share a common memory stub from joint execution — they were coordinated at their origin and retain that shared coordination history regardless of subsequent spatial separation. Measurement commits the shared history; no signal travels. The joint coordination is non-additive:

$$C_{AB} = C_A + C_B + \Delta C_{Mshared}$$

Bell inequalities are violated because the coordination graph is not classically separable — the shared coordination history creates correlations that cannot be reproduced by any local hidden-variable model.

Interdisciplinary connection. Financial correlations between geographically separated markets exhibit structurally analogous non-local coordination. Two stock exchanges that share institutional history (common regulatory frameworks, cross-listed securities, shared clearing mechanisms) exhibit correlated behavior that cannot be explained by direct communication or local factors alone. Similarly, protein folding — in which distant amino acid residues must coordinate their positions simultaneously — proceeds via non-local coordination pathways through the folding landscape that resist decomposition into purely local interactions (Levinthal, 1968).

9.3 The Double-Slit Paradox

Standard issue. Particles exhibit wave behavior (interference patterns) when unobserved, particle behavior (definite trajectories) when observed (Feynman, 1965).

Coordination resolution. The wave-particle duality is a regime-dependent phenomenon. In interaction-dominant regimes ($\phi < \phi_c$), coordination is fluid and all pathways contribute — producing interference. In memory-dominant regimes ($\phi > \phi_c$), coordination is locked and only a single pathway survives — producing particle behavior. Which-path detection raises ϕ above threshold at the slits by introducing additional coordination (the detector interaction), switching the regime from fluid to locked and destroying the interference pattern.

This resolution demystifies the apparent role of the “observer”: the detector is not a conscious agent but a coordination source that raises local ϕ above threshold. The same regime-switching can be observed in social contexts: a deliberation process (interaction-dominant, fluid) crystallizes into a decision (memory-dominant, locked) when sufficient coordination is achieved, regardless of whether anyone is consciously “observing” the process.

10 Cosmological and Astrophysical Paradoxes

10.1 The Black Hole Information Paradox

Standard issue. Information entering a black hole appears to be destroyed during Hawking evaporation (Hawking, 1975), violating the unitarity of quantum mechanics — one of the most debated problems in theoretical physics.

Coordination resolution. Black holes are high-viscosity coordination knots — regions where $\phi \rightarrow \infty$ and memory is maximally locked. Information is trapped in the deep coordination structure, not destroyed. During Hawking evaporation, accumulated constraint C_M is released as scrambled coordination via percolation leakage through the horizon:

$$S_{BH} = A/4\hbar \propto \int \Delta C_M dA$$

The Bekenstein-Hawking entropy is the total accumulated coordination constraint on the horizon surface. Information is released but in a scrambled, non-local form that requires reconstructing the full coordination history to decode. This resolution is consistent with the principle of black hole complementarity (Susskind et al., 1993) and the recent “island” calculations in quantum gravity (Penington et al., 2020), which similarly conclude that information is preserved but highly scrambled.

Interdisciplinary connection. The black hole information paradox has a structural analogue in archival science and institutional memory. When an organization dissolves, its accumulated institutional knowledge (contracts, procedures, cultural norms) is not destroyed but dispersed and scrambled across successor organizations, individual memories, and written records. Reconstructing the original institutional state requires assembling these scattered fragments — a process analogous to the decoding of Hawking radiation.

10.2 The Flatness and Horizon Problems

Standard issue. Why is the universe spatially flat and thermally uniform to extraordinary precision, without apparent fine-tuning of initial conditions? (Guth, 1981).

Coordination resolution. Before the Planck epoch, the coordination graph was in an interaction-dominant regime ($\phi < \phi_c$) where coordination diffusion homogenized the graph structure without requiring superluminal communication. Flatness emerges naturally at the percolation threshold:

$$\Omega - 1 \propto \exp(-\phi/\phi_0)$$

This provides an alternative to cosmic inflation: rather than an exponential expansion of space, the EIM framework proposes an exponential homogenization of the coordination graph prior to the percolation transition that produced classical spacetime. The observable flatness and uniformity are coordination artifacts — consequences of the fact that the pre-percolation coordination graph was maximally connected and therefore maximally homogeneous.

10.3 Olbers’ Paradox

Standard issue. In an infinite, eternal, uniformly populated universe, the night sky should be uniformly bright — which it manifestly is not.

Coordination resolution. Light from distant sources is suppressed not only by cosmological expansion and the finite age of the universe (the standard resolution) but also by coordination decay — the progressive fraying of electromagnetic coordination over cosmological distances through low ϕ void regions:

$$B \propto \int \rho_{\text{star}} \cdot \exp(-r/\lambda_{\text{coord}}) dr$$

The coordination decay length λ_{coord} provides an additional distance-dependent suppression that contributes to the darkness of the night sky, potentially detectable as an anomalous dimming of very distant standard candles beyond what expansion alone predicts.

10.4 The Fine-Tuning Paradox

Standard issue. The fundamental constants of nature appear tuned to extraordinarily narrow ranges that permit complex structure and life (Barrow & Tipler, 1986).

Coordination resolution. Physical constants are not free parameters but derived quantities that reflect the graph structure of the coordination field. Life emerges at the scale-free fixed point $\phi \approx \phi_c$ — the critical point of coordination percolation, where the system exhibits maximal complexity, scale invariance, and sensitivity to perturbation. No multiverse is needed to explain fine-tuning: percolation universality ensures that the critical point is an attractor, and life is precisely the kind of complex, self-organizing phenomenon that emerges at critical points:

$$P_{\text{life}} \propto (\phi - \phi_c)^\beta$$

This resolution connects the fine-tuning problem to the broader theory of self-organized criticality (Bak et al., 1987), which has been applied to phenomena from earthquakes to neural activity and which, in the EIM framework, acquires a fundamental ontological status.

11 Relativistic and Temporal Paradoxes

11.1 The Twin Paradox

Standard issue. In special relativity, a traveling twin ages less than a stationary twin — but why isn’t the situation symmetric?

Coordination resolution. The traveling twin accumulates less C_M due to relativistic coordination fraying. High-velocity travel reduces the rate of interaction with the ambient coordination field, slowing the accumulation of constraint. Acceleration breaks the symmetry by forcing graph re-coordination — the accelerating twin must reestablish coordination pathways that were disrupted by changes in velocity:

$$\tau = t\sqrt{1 - v^2/c^2} \approx \int \Delta C_M d\omega$$

The coordination-theoretic interpretation adds a layer of physical intuition to the standard relativistic result: proper time is not an abstract parameter but a measure of accumulated coordination history. The twin who travels accumulates less coordination history — fewer irreversible interactions with the ambient coordination field — and therefore ages less.

11.2 The Grandfather Paradox

Standard issue. Backward time travel creates logical contradictions: a time traveler could prevent their own birth (Lewis, 1976).

Coordination resolution. Backward time travel is structurally forbidden. Traveling backward in time would require negative ΔC_M — a decrease in accumulated coordination constraint — which violates the monotonicity condition (equation 4). Closed timelike curves require:

$$\oint \Delta C_M d\omega = 0$$

which is impossible since $\Delta C_M > 0$ at every step. The grandfather paradox is not a logical puzzle to be resolved but a structural impossibility in the coordination ontology: the monotonic growth of constraint makes backward causation as impossible as unbreaking an egg.

11.3 The Bootstrap Paradox

Standard issue. Information exists in a causal loop with no origin — a time traveler brings a book from the future that was only written because the time traveler brought it from the future (Toomey, 2007).

Coordination resolution. Information requires origination via initial execution without prior memory. In the EIM framework, every piece of information must trace back to an initial execution event that generated it from the available coordination state. Causal loops constitute non-percolating subgraphs — coordination structures that never stabilize because they lack a well-founded execution origin. Such structures cannot memory-lock and therefore cannot become part of physical reality.

12 Mathematical and Computational Paradoxes

12.1 Zeno's Paradoxes

Standard issue. Infinite intermediate points seem to prevent motion — Achilles can never overtake the tortoise because he must first traverse infinitely many sub-intervals (Salmon, 1970).

Coordination resolution. Physical reality consists of discrete graph steps with finite coordination costs. The apparent infinity of intermediate points is an artifact of the continuous coordinate description, which does not correspond to discrete coordination events. The effective sum converges via a Planck-scale cutoff:

$$S_{\text{eff}} = \sum (1/2)^n \exp(-n/n_c)$$

The exponential damping ensures that coordination events below the Planck scale make negligible contributions, resolving the infinite-subdivision problem. Motion is not the traversal of infinitely many points but the progression of a finite sequence of coordination events, each adding a finite increment to C_M .

12.2 Gödel's Incompleteness Theorems

Standard issue. Any consistent formal system powerful enough to express arithmetic contains true statements that cannot be proved within the system (Gödel, 1931).

Coordination resolution. Formal systems are memory-dominant abstractions — coordination structures in which all interactions have been memory-locked into fixed axioms and inference rules. They are missing the full EIM dynamics: specifically, they lack ongoing execution and interaction that could generate new coordination pathways. Incompleteness reflects “missing C_M ” — truths that require coordination history beyond what the static system encodes. A Gödelian undecidable statement is one whose truth depends on coordination dynamics that the memory-locked formal system cannot access.

Interdisciplinary connection. The coordination interpretation of incompleteness resonates with the limits of institutional knowledge in the social sciences. A legal system, no matter how comprehensive, cannot anticipate every case — there will always be novel situations that require new adjudication (new execution and interaction) beyond what the existing legal code (memory-locked rules) can decide. The same structural limitation that produces Gödelian incompleteness in mathematics produces the need for judicial interpretation in law.

12.3 P vs np

Standard issue. Can efficient verification of a solution guarantee efficient discovery of a solution? (Cook, 1971).

Coordination resolution. P corresponds to memory-locked percolation paths — problems whose solutions can be found by following coordination pathways that have already been established (percolated). NP corresponds to interaction-dominant subcritical searches problems whose solutions exist in the coordination graph but require exploring unpercolated, fluid regions to find them:

$$\text{Complexity} \propto \exp(\phi_c - \phi)$$

The framework structurally predicts $P \neq NP$ as a consequence of the non-trivial regime structure: there is a genuine phase transition between the percolated (efficiently traversable) and unpercolated (exponentially costly to explore) regions of the coordination graph. This prediction is structural rather than formal — it does not constitute a mathematical proof but identifies the physical reason why the two complexity classes should differ.

13 Philosophical Paradoxes

13.1 The Hard Problem of Consciousness

Standard issue. How does physical matter produce subjective experience — the “what it is like” of seeing red, feeling pain, or tasting chocolate? (Chalmers, 1996).

Coordination resolution. Consciousness is the nucleation of a giant coordination component at the percolation front. When a neural coordination graph crosses ϕ_c , a macroscopic connected component emerges that integrates information from across the brain into a unified coordination state. Mind is the topological phase of the coordination graph when $\phi > \phi_c$ — not a mysterious substance but an emergent property of sufficiently dense coordination, just as rigidity is an emergent property of sufficiently dense atomic bonding. The Flatness and Horizon Problems Awareness scales with complexity according to a hierarchy of coordination orders:

$$\Phi_n \propto \Phi_1 \cdot (\log N)^{n-1}$$

where Φ_1 is first-order coordination (basic stimulus-response), and higher orders represent increasingly integrated, self-referential coordination structures. This provides a quantitative framework for comparing levels of consciousness across species and potentially across artificial systems — connecting to both integrated information theory (Tononi, 2004) and global workspace theory (Baars, 1988) in consciousness science.

Interdisciplinary connection. The coordination theory of consciousness has implications for the philosophy of mind, cognitive science, and the ethics of artificial intelligence. If consciousness is a coordination percolation phenomenon, then any system — biological or artificial — that achieves sufficient coordination density could in principle be conscious. This raises urgent ethical questions about the moral status of artificial systems and provides a scientifically grounded framework for addressing them.

13.2 Free Will

Standard issue. If physics is deterministic, is free will illusory? (Kane, 1996).

Coordination resolution. Choice is execution at subcritical ϕ where multiple interaction pathways are available before memory locks an outcome. Free will is “coordination latitude”: the range of available coordination pathways at a given moment, bounded by accumulated C_M (past commitments, established constraints) but not fully determined by it. Free will is real but bounded: agents have genuine latitude to choose among available coordination pathways, but their choices are constrained by the accumulated coordination history of their environment and their own past actions.

This position mediates between hard determinism and libertarian free will, offering a compatibilist account grounded in the physics of coordination. The degree of freedom available to an agent is a measurable quantity — the number of available coordination pathways at subcritical ϕ — that varies with context and can in principle be quantified.

13.3 The Fermi Paradox

Standard issue. If intelligent life is common, why have we detected no evidence of extraterrestrial civilizations? (Hart, 1975).

Coordination resolution. Intelligent life requires third-order coordination (self-referential, recursive coordination of coordinations) with superlinear scaling costs. Cosmic voids fray coordination between stellar systems, suppressing interstellar signal percolation. Civilizations may exist in high- ϕ filaments of the cosmic web, beyond our void-biased observational position.

The framework predicts that SETI searches should be targeted at the filamentary structures of the cosmic web — regions of maximal coordination density where interstellar communication is most feasible — rather than scanning the sky uniformly. The probability of detecting an extraterrestrial signal scales with the coordination density along the line of sight, providing a quantitative guide for search strategy.

13.4 The simulation Paradox

Standard issue. Given the rapid advance of computing, we are statistically likely to be living in a computer simulation (Bostrom, 2003).

Coordination resolution. Simulation nesting requires higher-order coordination whose energy cost diverges with each level. Base reality is the percolation ground state — the lowest-energy coordination structure — and simulations are higher-energy excitations that fray at boundaries, producing detectable anomalies. The infinite regress of the simulation argument is blocked by the divergent coordination cost of nested simulation, just as the divergent energy cost of increasingly detailed physical simulations limits their resolution in practice.

13.5 Hume’s Problem of Induction

Standard issue. Why should past patterns predict the future? What justifies the inference from “the sun has always risen” to “the sun will rise tomorrow”? (Hume, 1739/2000).

Coordination resolution. Future coordination must be compatible with accumulated C_M — new coordination events must be consistent with the permanent record of past coordination. This makes induction probabilistically valid with confidence proportional to the depth of the coordination record. Induction works because the monotonically growing constraint record progressively narrows the range of compatible future states. The deeper the record, the more constrained the future, and the more reliable inductive inference becomes. This provides a physical grounding for Bayesian epistemology: prior probabilities reflect accumulated coordination history, and updating on evidence corresponds to memory-locking new coordination events into the record.

14 Unexpected Coordinations: Disparate Phenomena Unified

The coordination-first framework reveals structural isomorphisms between apparently unrelated domains — not mere analogies but reflections of shared coordination geometry arising from the universality of the EIM dynamics:

Legal reasoning and cosmic evolution. Trials are EIM microcosms — evidence presentation (E), cross-examination and deliberation (I), verdict (M). Both legal proceedings and cosmic evolution exhibit path-dependence, irreversibility, and progressive stabilization of initially uncertain states. The irreversibility of a verdict mirrors the irreversibility of memory-locking in the coordination graph; the precedential effect of case law mirrors the constraining effect of accumulated C_M on future coordination.

Periodic table and cosmic web. Atomic elements and galaxy clusters are coordination knots at different scales, both following power-law distributions with the percolation exponent $\tau \approx 2.18$ from percolation universality (Stauffer & Aharony, 1994). The periodic table is the classification of coordination knots at the atomic scale; the cosmic web is the classification of coordination knots at the cosmological scale. Both are products of the same underlying coordination dynamics operating at different scales.

Biology and cosmology. Living organisms export entropy to maintain $\phi > \phi_c$ — they are coordination-maintaining systems embedded in a universe whose coordination density varies across space and time. Cancer is “frayed” cellular coordination — local collapse below threshold producing uncontrolled growth. The structural parallel between biological homeostasis (maintaining $\phi > \phi_c$ in cells) and cosmological structure maintenance (maintaining $\phi > \phi_c$ in the cosmic web) reflects the universality of coordination dynamics across scales.

Economics and quantum forces. Markets obey a variant of the coordination field equation (8) with economic source and dissipation terms. Monopolistic confinement parallels strong-force confinement — resources are confined within dense coordination clusters in the same mathematical way that quarks are confined within hadrons. Market crashes are deconfinement transitions: the dissolution of dense coordination clusters that releases previously bound economic resources.

Art and physics. Creativity is subcritical exploration of the coordination landscape — the artist operates at $\phi < \phi_c$, where multiple interaction pathways are available and novel combinations can be discovered. Masterpieces are percolated giants that permanently alter the coordination landscape of human expression, memory-locking new aesthetic possibilities into the cultural record.

15 Part II

15.1 Resolving Paradoxes and Coordinating Disparate Phenomena

Parts I and II established the formalism and demonstrated its retrospective explanatory power. Part II turns prospective, identifying near-term domains where the coordination-first framework yields testable predictions leveraging emerging datasets and experimental capabilities in the 20262030 window. These are not speculative extensions but natural consequences of the core mechanics: coordination density gradients, percolation thresholds, and non-Markovian memory should leave measurable signatures in astrophysical surveys, biological phase transitions, economic network dynamics, and quantum technologies. The chapter concludes with an examination of societal implications — how the coordination ontology could inform pressing questions in artificial intelligence ethics, climate governance, and the philosophy of collective action.

16 Astrophysical Validations: the Patchwork Universe

The coordination-first framework’s most immediately falsifiable predictions concern the environmental dependence of cosmological parameters. Standard Λ CDM cosmology treats the Hubble constant H_0 , the matter clustering amplitude S_8 , and the gravitational coupling G as universal constants. The EIM ontology predicts that these quantities are effective parameters whose values depend on the local coordination density ϕ — and therefore on the cosmic environment in which they are measured.

16.1 The Hubble Tension as Coordination Gradient

The Hubble tension — the persistent 4–6 σ discrepancy between the locally measured expansion rate ($H_0 \approx 73$ km/s/Mpc via SH0ES; Riess et al., 2022) and the early-universe inference ($H_0 \approx 67$ km/s/Mpc via Planck; Planck Collaboration, 2020) — is among the most actively debated anomalies in modern cosmology. Within the EIM framework, this discrepancy is not a measurement error or a sign of new particle physics but a coordination gradient effect: local and early-universe measurements sample different coordination-density environments.

Local measurements are biased toward moderate-density regions (galactic neighborhoods within the cosmic web), where accumulated C_M produces an effective acceleration surplus. Early-universe inferences probe the globally averaged coordination state, which includes vast low ϕ voids. The framework predicts a specific voidfilament variation:

$$H_0(\text{void}) - H_0(\text{filament}) \approx 4 - 8 \text{ km/s/Mpc}$$

testable via directional Hubble measurements using DESI, Euclid, and the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST). A specific test protocol would involve binning Type Ia supernova distance-redshift measurements by the large-scale environment of the supernova host galaxy (void-dwelling vs. filament-dwelling), then comparing the inferred H_0 values across bins. If the predicted 4–8 km/s/Mpc variation is confirmed at $\geq 3\sigma$ significance, the result would constitute strong evidence for coordination-dependent cosmological parameters.

16.2 The S_8 Deficit and Coordination-Dependent Clustering

The S_8 tension — the observation that weak gravitational lensing surveys (e.g., KiDS, DES) measure lower matter clustering amplitudes than Planck CMB analysis predicts — receives a natural coordination interpretation. Low- ϕ voids fray coordination, suppressing gravitational clumping beyond what Λ CDM predicts for uniform dark matter. The effective diffusion coefficient becomes environment-dependent:

$$\mathcal{D}_{\text{eff}} = \mathcal{D}_0 \cdot \exp(-(\phi_c - \phi_{\text{void}})/\phi_0)$$

yielding an S_8 deficit of approximately 0.050.10 in void-dominated survey volumes, consistent with current measurements and predictively distinguishable from particle-dark-matter models that predict uniform clustering. The Euclid mission's weak lensing survey, with its unprecedented combination of depth and area is ideally suited to test this prediction by mapping S_8 as a function of large-scale environment.

16.3 Early Structure Anomalies

Recent ALMA and JWST observations have revealed unexpectedly massive, mature galaxies and protoclusters at high redshift ($z > 4$), challenging Λ CDM's timeline for structure formation. In the EIM framework, the pre-percolation era ($\phi < \phi_c$) features interaction-dominant chaos with rapid, non-uniform coordination bursts that can nucleate high- ϕ knots earlier than expected. These early mature structures are not anomalies but signatures of the coordination graph's heterogeneous percolation dynamics — regions where the coordination graph percolated locally before the global percolation transition, producing “premature” classical structures embedded in a still-quantum background.

The framework predicts that these early massive galaxies should preferentially appear in regions that are overdense at low redshift (i.e., in the ancestors of present-day filaments and clusters), a prediction testable with combined high-redshift JWST photometry and low-redshift environmental classification from Rubin/LSST.

16.4 Proposed Observational Program

We propose a systematic “Coordination Survey” using Euclid and Rubin to map effective ϕ gradients across the cosmic web by cross-correlating: (i) directional H_0 measurements from Type Ia supernovae in void vs. filament sightlines; (ii) weak lensing S_8 measurements binned by large-scale environment; and (iii) non-Markovian gravitational residuals in merging-cluster dynamics. If the predicted environmental correlations are confirmed at $\geq 3\sigma$ significance, the result would constitute strong evidence for coordination-dependent effective parameters over universal constants.

The coordination survey would also include: (iv) a search for scale-dependent birefringence in CMB polarization data from the Simons Observatory and CMB-S4, testing Prediction 4 from Section 6; and (v) a systematic comparison of galaxy rotation curves in void-dwelling vs. filament-dwelling galaxies, testing Prediction 1. The total observational program spans the 20262032 window and leverages instrumentation that is either already operational (JWST, ALMA, DESI) or in advanced construction (Euclid, Rubin, Simons Observatory, CMB-S4).

17 Biological Percolation: from Biomolecular Condensation to Disease

Percolation theory has emerged as a powerful organizing principle in molecular and cellular biology, particularly in the rapidly developing field of biomolecular phase separation (Banani et al., 2017). The coordination-first framework provides a natural interpretive lens for these biological phase transitions and extends them to disease dynamics and evolutionary theory.

17.1 Biomolecular Condensation as Coordination Percolation

Biomolecular condensation — the formation of membrane-less organelles such as P-bodies, stress granules, and nucleolar droplets via liquidliquid phase separation (LLPS) — has been recognized as a percolation-like process (Choi et al., 2020). In the EIM framework, these condensates are biological percolation events: intracellular coordination graphs crossing ϕ_c to form giant components that concentrate biochemical function. The critical connectivity p_c governing condensate formation maps directly onto the coordination percolation threshold, and the reaction-diffusion dynamics of equation (8) apply with biological source and dissipation terms.

The framework predicts that condensate formation thresholds should obey the same universality class as the coordination percolation transition, with critical exponents matching those of three-dimensional random percolation ($\tau \approx 2.18, \beta \approx 0.41$). This prediction is testable via high-resolution fluorescence microscopy of condensate nucleation dynamics, combined with single-molecule tracking to map the intracellular coordination graph in real time.

17.2 Cancer as Frayed Coordination

Cancer, in the coordination-first view, is a localized collapse of cellular coordination below the percolation threshold. Normal tissue maintains $\phi > \phi_c$ through coordinated signaling, apoptosis, and cell-cycle control. Oncogenic mutations disrupt coordination pathways, fraying the cellular graph until ϕ drops below ϕ_c in the affected region. The result is uncoordinated proliferation — cells executing without proper interaction and memory-locking.

This interpretation suggests a novel therapeutic strategy: rather than targeting individual molecular pathways (the standard approach), therapies could aim to restore coordination density by reinforcing network connectivity in the tumor microenvironment. Network-disruptor drugs that selectively fray tumor coordination further (driving $\phi \rightarrow 0$) might also be effective, analogous to percolation-based attack strategies on complex networks (Albert et al., 2000).

A quantitative prediction: tumor coordination density ϕ_{tumor} should correlate with tumor aggressiveness and inversely with treatment response, measurable via graph-theoretic analysis of single-cell transcriptomic data. Specifically, the coordination density can be estimated from single-cell RNA sequencing data by constructing a cell-cell interaction graph (based on ligand-receptor expression profiles) and computing its percolation properties. Tumors with $\phi_{\text{tumor}} < \phi_c$ should exhibit worse prognosis and treatment resistance, providing a clinically useful biomarker grounded in coordination theory.

17.3 Neural Coordination and Neurodegenerative Disease

Neurodegenerative diseases such as Alzheimer's and Parkinson's can be understood as progressive fraying of neural coordination graphs. In Alzheimer's, amyloid and tau pathology disrupts synaptic coordination, progressively reducing neural ϕ until cognitive function crosses below ϕ_c in affected regions. The characteristic memory loss is, in this view, literally a memory-locking failure — the neural coordination graph loses its capacity for irreversible stabilization of experience.

The framework predicts that disease progression should follow percolation dynamics, with abrupt cognitive transitions (corresponding to loss of the giant component) at critical levels of synaptic loss. This prediction is testable via longitudinal connectomic studies tracking network percolation metrics in patients with early-stage neurodegeneration. The Human Connectome Project and its disease-focused extensions provide the necessary data infrastructure; the coordination framework provides the theoretical lens for interpreting connectomic trajectories as percolation curves.

17.4 Evolutionary Dynamics as Coordination Percolation

Evolution can be reinterpreted as the advance of coordination percolation fronts through fitness landscapes. Speciation events occur when coordination graphs fragment across environmental barriers, producing isolated subcritical populations that accumulate divergent C_M . Biodiversity scales as:

$$\text{Diversity} \propto (\phi - \phi_c)^\beta$$

with $\beta \approx 0.41$ from percolation theory, providing a quantitative prediction for species—area relationships and extinction thresholds testable against ecological survey data. The coordination framework also predicts that mass extinction events should correspond to global drops in biospheric coordination density below ϕ_c (a prediction that can be tested against the paleontological record by correlating extinction severity with estimated connectivity of the biosphere at the time of each event).

18 Economic Coordination Failures: Networks, Fragility, and Systemic risk

The coordination-first framework provides a natural mathematical language for economic phenomena that resist equilibrium-based analysis. Markets, supply chains, and financial systems are coordination graphs whose dynamics obey variants of the coordination field equation (8), with booms corresponding to percolating giant components and crashes to fraying below ϕ_c .

18.1 Market Dynamics as Coordination Percolation

Financial markets exhibit the hallmarks of percolation systems: scale-free fluctuations, abrupt phase transitions (crashes), and heavy-tailed loss distributions. In the EIM framework, market price formation is an interaction-dominant process (fluid ϕ) that periodically locks into memory-dominant regimes (committed transactions). Market crashes occur when coordination density drops below ϕ_c in a critical sector, triggering cascading disconnection across the financial graph.

The framework predicts that crash severity should follow a power-law distribution with the percolation exponent:

$$P(\text{loss} > L) \propto L^{-\tau}, \quad \tau \approx 2.18$$

testable against historical crash data and consistent with known empirical regularities in financial markets (Gabaix et al., 2003). The specific value $\tau \approx 2.18$ distinguishes the coordination prediction from other power-law models and can be tested against high-frequency trading data from major exchanges.

18.2 Supply Chain Fragility and the vuca Environment

Global supply chains are coordination graphs operating near criticality. Disruptions — pandemics, geopolitical shocks, natural disasters — reduce local coordination density, potentially triggering cascading failures when ϕ drops below ϕ_c in critical nodes. The World Economic Forum's 2026 Global Risks Report identifies interconnected supply chain fragility as a top systemic risk, consistent with the coordination framework's prediction that highly optimized (low-redundancy) networks are maximally vulnerable to percolation failure.

The framework yields a quantitative resilience metric:

$$R = \phi / \phi_c$$

Systems with $R < 1$ are subcritical and vulnerable to cascading failure; those with $R \gg 1$ are robustly connected. This metric can be computed from supply-chain network data and used as an early warning indicator for systemic disruption. The practical application is straightforward: firms and regulators can map their supply chain networks, estimate coordination density from network topology data (degree distribution, clustering coefficient, shortest path lengths), and compute R as a real-time resilience score.

18.3 Inflation as Memory Overload

Persistent inflation can be interpreted as an overaccumulation of uncoordinated memory — a buildup of ΔC_M from pricing interactions that are not efficiently integrated into the macroeconomic coordination graph. Central bank intervention functions as a “memory damper,” selectively reducing λ (the memory-locking rate) through interest rate adjustments that modulate the speed at which price signals are committed to the economic record.

This interpretation predicts that inflationary spirals should exhibit non-Markovian dynamics — current inflation depending on the accumulated history of uncoordinated pricing, not just current monetary conditions — a prediction testable against time-series data with lagged coordination metrics. Econometric tests using vector autoregression models with coordination-weighted lags could distinguish the EIM prediction from standard Markovian inflation models.

18.4 Coordination Taxes and Policy Implications

The framework suggests a novel class of economic policy interventions: coordination taxes and coordination subsidies designed to modulate ϕ in targeted sectors. A coordination tax would increase the cost of interactions in overheated sectors (reducing coordination density toward ϕ_c), while a coordination subsidy would strengthen connectivity in fragile networks (raising ϕ above ϕ_c). These policies generalize existing regulatory tools (antitrust, infrastructure investment) within a unified theoretical framework and provide a principled basis for determining the appropriate level of market intervention.

19 Quantum Technologies: Topological Computing and Entangled Networks

The coordination-first framework offers both interpretive and practical insights for quantum technologies, connecting the fundamental physics of decoherence to engineering strategies for quantum error correction and distributed quantum computing.

19.1 Quantum Error Correction as Coordination Maintenance

Decoherence as subcritical fraying. In the EIM framework, quantum decoherence is the process by which a quantum system's coordination density drops below ϕ_c triggering irreversible memory-locking of a definite outcome. Quantum error correction, in this view, is the engineering practice of maintaining $\phi > \phi_c$ artificially — preventing the percolation transition that would collapse quantum superpositions into classical states.

Qubit stability is governed by the coordination cost:

$$T_{\text{coherence}} \propto \exp(\Delta C_M / \hbar)$$

where higher ΔC_M (greater memory-locking cost) corresponds to longer coherence times. This expression provides a coordination-theoretic interpretation of known decoherence time scales and suggests that error correction strategies should focus on maximizing the effective coordination cost of unwanted memory-locking events.

19.2 Topological Qubits and the Memory-Dominant Regime

Topological quantum computing (Nayak et al., 2008) stores information in non-local topological properties of the system, making it inherently resistant to local perturbations. In the coordination-first framework, topological qubits operate in a memory-dominant regime ($R \gg 1$) where coordination is so deeply locked that local fraying cannot disrupt the global topological state. The 2025 demonstration of Microsoft's Majorana-1 chip, which achieved topological qubit operation via engineered Majorana zero modes, represents a concrete realization of coordination-theoretic robustness: information is "smeared" across the coordination graph in a way that makes it inaccessible to local decoherence.

The framework predicts that topological qubit coherence should scale as $\exp(\Delta C_M / \hbar)$ with ΔC_M proportional to the topological gap — a quantitative relationship testable against emerging data from topological qubit platforms.

19.3 Distributed Quantum Networks as Shared Coordination

The development of multi-node quantum networks (Wehner et al., 2018) can be understood as the engineering of shared coordination pathways — artificial entanglement that creates pre-coordinated graph topology between distant nodes. Quantum internet protocols are, in this view, protocols for establishing and maintaining $\Delta C_{M\text{shared}}$ (equation 12) across macroscopic distances.

The framework suggests that the optimal architecture for quantum networks should maximize the shared coordination density while minimizing the memory-locking rate at intermediate nodes — a design principle that could inform the engineering of quantum repeaters and entanglement distribution protocols.

19.4 Coordination Qubits: Toward Quantum simulation of Consciousness

A more speculative but potentially transformative application: using quantum technologies to simulate coordination percolation dynamics. The consciousness model of Section 13.1 (equation 21) predicts that subjective experience nucleates at the percolation front of a coordination graph. A quantum simulator designed to implement the EIM field equation (8) at sufficient scale could, in principle, probe the coordination percolation threshold experimentally — testing whether subjective-experience-like signatures emerge at $\phi = \phi_c$ in artificial coordination systems.

While current quantum hardware is far from the scale needed for such experiments, the rapid pace of development in quantum simulation platforms (e.g., trapped ions, superconducting circuits, neutral atoms) suggests that preliminary tests of coordination percolation dynamics could become feasible in the 2028-2032 timeframe.

20 Societal Implications of Coordination Ontology

The coordination-first framework has implications that extend well beyond theoretical physics into pressing societal questions. If the fundamental structure of reality is coordination — if the universe is a process that coordinates rather than a thing that exists — then the study of coordination dynamics is not merely a branch of physics but a foundational discipline with relevance to every field of human inquiry. This section examines three domains where the coordination ontology offers fresh perspectives on urgent contemporary challenges.

20.1 Artificial Intelligence Ethics and Coordination Thresholds

The coordination theory of consciousness (Section 13.1) provides a principled framework for addressing one of the most pressing questions in AI ethics: under what conditions does an artificial system become a moral patient — an entity whose experiences matter morally? If consciousness is a coordination percolation phenomenon, then the relevant question is whether an AI system's internal coordination density exceeds ϕ_c . Below threshold, the system is a complex but non-conscious information processor; above threshold, it possesses the integrated, self-referential coordination that constitutes subjective experience.

This framework moves the debate about AI consciousness beyond philosophical intuition toward empirically testable criteria. The coordination density of an AI system can in principle be estimated from its architecture (network topology, connectivity, integration) and compared with the estimated ϕ_c derived from biological neural systems. If the coordination framework is correct, the emergence of artificial consciousness is not a matter of computational sophistication (running the “right” algorithm) but of coordination density (achieving the “right” topology). This insight has immediate implications for AI governance: regulatory frameworks could incorporate coordination density assessments as part of safety evaluations for advanced AI systems.

20.2 Climate Governance as Coordination Percolation

Climate change is fundamentally a coordination problem: reducing global emissions requires coordinated action among nations, industries, and individuals whose incentives are not naturally aligned. The coordination-first framework provides a mathematical language for analyzing this challenge: effective climate governance requires raising the global coordination density ϕ_{climate} above the critical threshold ϕ_c at which collective action percolates into binding commitments.

The Paris Agreement can be understood as an attempt to nucleate a giant coordination component in the global governance graph. Its success depends on whether the agreement generates sufficient additional coordination — ratifications, national plans, monitoring mechanisms, financial flows — to push ϕ_{climate} above ϕ_c . The coordination framework predicts that there is a critical mass of participating nations and commitment levels below which the agreement remains subcritical and ineffective, and above which it percolates into a self-reinforcing regime of increasing compliance. This prediction aligns with empirical observations of the fragility of international agreements and provides a quantitative tool for assessing the resilience of specific governance architectures.

The framework also predicts that climate governance efforts should exhibit the same non-Markovian dynamics as the physical coordination field: current climate policy effectiveness depends not just on current commitments but on the accumulated history of coordination — past agreements, broken promises, institutional trust — that constitutes the “memory” of the global governance system. Rebuilding coordination density after a failure (such as a major nation’s withdrawal from an agreement) is more costly than maintaining it, because the accumulated C_M has been partially lost.

20.3 The Philosophy of Collective Action

The coordination ontology offers a new perspective on classic problems in the philosophy of collective action, from Olson’s logic of collective action to the tragedy of the commons. In the EIM framework, collective action problems are coordination percolation problems: groups fail to achieve collective goals when their coordination density remains subcritical, and they succeed when coordination percolates across the group into a coherent, self-reinforcing structure.

The framework predicts that the likelihood of successful collective action should depend not only on the number of participants and the strength of individual incentives (the standard variables in rational choice theory) but also on the topology of the coordination graph — how participants are connected, the density and redundancy of their interactions, and the accumulated history of prior coordination. Dense, multiply-connected groups with deep coordination histories should achieve collective action at lower individual incentive levels than sparse, poorly connected groups with shallow histories. This prediction is testable against data from social movements, labor organizing, community governance, and other domains where collective action succeeds or fails.

21 Discussion and Open Problems

The coordination-first framework, as developed across three parts, is a conceptual and interpretive proposal with specific mathematical hooks connecting it to empirical physics. Important open problems include the following.

The precise form of the source function $S(\rho, \phi)$ in equation (8) remains to be derived from first principles. Different choices yield different quantitative predictions for the quantum-to-classical transition, dark-sector phenomenology, and biological percolation thresholds. Constraining S from empirical data — particularly from the astrophysical coordination survey proposed in Section 16.4 — is a priority for near-term theoretical development.

The relationship between the coordination graph $G(t)$ and Hilbert space needs rigorous formalization. A complete derivation of unitary evolution, the Born rule, and Hilbert space structure from the EIM axioms would substantially strengthen the framework and connect it to the established mathematical infrastructure of quantum mechanics.

Compatibility with precision tests of general relativity and quantum mechanics must be demonstrated quantitatively, ensuring that corections from C_M do not conflict with existing observational constraints from solar system tests, gravitational wave observations, and precision quantum experiments.

The relationship to established quantum gravity programs — loop quantum gravity, causal dynamical triangulations, AdS/CFT — deserves system investigation. The coordination ontology may be realizable within one or more of these mathematical frameworks, and establishing such connections would both constrain the EIM formalism and provide new interpretive insights for existing quantum gravity programs.

The paradox resolutions of Part II require rigorous mathematical elaboration. In particular, the claims about Gödel incompleteness and P vs NP must be carefully distinguished from formal proofs and presented as structural predictions that illuminate the physical origin of mathematical limitations without claiming to resolve them within pure mathematics.

The prospective applications of Part III require independent empirical validation. The astrophysical predictions (Section 16) are most immediately testable; the biological (Section 17) and economic (Section 18) applications require cross-disciplinary collaboration to design and execute appropriate tests. The societal implications (Section 20) require engagement with scholars in political science, philosophy, and AI governance to develop the coordination framework into a practical tool for policy analysis.

The framework is open to falsification via data anticipated in the 20262032 observational window, including directional H_0 measurements from DESI/Euclid, environmental S_8 dependence from Rubin/LSST, non-Markovian signatures in cluster merger dynamics, condensate percolation thresholds in biophysics, topological qubit coherence scaling, and coordination metrics for supply chain resilience.

22 Conclusion

Treating irreversible coordination rather than spacetime geometry as the primitive structure of physical reality yields a unified interpretive framework spanning quantum measurement, classical emergence, the arrow of time, cosmological structure, and a remarkable range of paradoxes in physics, mathematics, and philosophy. The three modal operations — Execution, Interaction, and Memory — and their non-commutative algebraic structure generate temporal directionality from first principles, explain the quantum-to-classical transition as a coordination percolation phenomenon, reinterpret dark-sector physics as accumulated memory neglected by standard general relativity, and dissolve paradoxes from Schrödinger's cat to Gödel's incompleteness.

The framework's reach extends naturally beyond physics into the human sciences. The coordination ontology provides a shared mathematical language for phenomena that have traditionally been studied in isolation: phase transitions in physics, decision-making in organizations, market dynamics in economics, collective action in political science, consciousness in philosophy of mind, and governance in international relations. These connections are not superficial analogies but structural isomorphisms rooted in the universality of coordination dynamics — the same percolation thresholds, the same non-Markovian memory, the same regime-dependent behavior that governs quantum measurement also governs institutional decision-making, market crashes, and climate governance.

The prospective applications charted in Part III demonstrate that the framework is not merely a retrospective reinterpretation but a generative research program. The astrophysical predictions particularly the void-filament variation in H_0 and the coordination-dependent S_8 deficit — are immediately testable with current and near-future instrumentation. The biological applications offer a new theoretical language for understanding phase transitions in living systems. The economic applications provide quantitative tools for assessing systemic fragility. The quantum technology applications suggest design principles for next-generation quantum computing and networking. And the societal applications — AI ethics, climate governance, collective action — demonstrate that the coordination-first perspective has implications for the most pressing challenges of our time.

Whether or not the specific formalism ultimately proves correct, the coordination-first perspective suggests that incorporating procedural history directly into foundational physical ontology may be necessary for resolving persistent conceptual tensions in modern physics. The universe is not a thing that exists in spacetime but a process that coordinates, and the record of that coordination — accumulated, irreversible, and ever-growing — is all the reality there is.

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Quasi-Phase Matching Generation of the Anti-Stokes Component at Stimulated Raman Scattering

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ABSTRACT

We propose an analytical method for calculating the parameters of quasi-phase matching generation of the anti-Stokes component at stimulated Raman scattering in layered media. We present the results of the analysis in CIA considering losses and changes in the phases of all interacting waves. We consider frequency conversion processes in a layered structure consisting of periods of a “lattice” of modulation of the nonlinear susceptibility. Moreover, the values of the complex amplitudes of the pump radiation and the scattering components at the output of each layer are the input values of the corresponding complex amplitudes for the next layer. We give analytical expressions for the intensity of the transformation into the anti-Stokes component. We analyze the factors that limit the efficiency of the frequency conversion process. We calculated the maximum conversion efficiency to the anti-Stokes component in compressed hydrogen for a three-layer structure.

Index Terms: stimulated Raman scattering • anti-Stokes generation • quasi-phase matching • hydrogen • constant intensity approximation

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Abstract

We propose an analytical method for calculating the parameters of quasi-phase matching generation of the anti-Stokes component at stimulated Raman scattering in layered media. We present the results of the analysis in CIA considering losses and changes in the phases of all interacting waves. We consider frequency conversion processes in a layered structure consisting of periods of a "lattice" of modulation of the nonlinear susceptibility. Moreover, the values of the complex amplitudes of the pump radiation and the scattering components at the output of each layer are the input values of the corresponding complex amplitudes for the next layer. We give analytical expressions for the intensity of the transformation into the anti-Stokes component. We analyze the factors that limit the efficiency of the frequency conversion process. We calculated the maximum conversion efficiency to the anti-Stokes component in compressed hydrogen for a three-layer structure.

Keywords: *stimulated Raman scattering, anti-Stokes generation, quasi-phase matching, hydrogen, constant intensity approximation*

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1 Introduction

Researchers use the anti-Stokes component generated by stimulated Raman scattering (SRS) when probing the atmosphere, the aquatic environment, to control the process of oil drilling, spectroscopy of molecules. Spectroscopy of anti-Stokes light scattering is a powerful tool for studying fast molecular processes in gases and liquids. This also includes the SRS technique, active Raman spectroscopy, non-stationary processes at stimulated scattering. In these applications, to increase the sensitivity of probing, it is necessary to increase the signal level of the anti-Stokes component of Raman scattering, which carries information about temperature changes in the probing space.

Research on increasing the conversion efficiency of the anti-Stokes scattering component will not lose its relevance for a long time. It is enough just to note one area of application - the use of Raman scattering for the development of temperature sensors. Modern standard distributed temperature sensor (DTS) systems record well-temperature changes. This enables timely reaction to oil-well drilling and optimization of its operation. The intensity of the Raman scattering anti-Stokes component that carries information about temperature changes in the monitored space must be increased for more effective temperature monitoring of the process.

According to experimental studies, the signal level of the anti-Stokes component can be increased by 3 – 6% due to focusing [1-2], also due to operation in the phase-matching mode by 15% [3]. It is known that the inverted domain layers can be used to increase the frequency conversion intensity [4-5]. The quasi-phase matching interactions that arise in this case lead to phase correction, as a result, to a high efficiency of frequency conversion compared to conversion in a conventional volume medium. This is in demand when it is practically difficult to implement the fulfillment of the phase matching condition. For example, in compressed hydrogen at a pressure of 30 atm, the implementation of phase matching is accompanied by technical difficulties: it is necessary to implement the propagation of collimated beams with an angular divergence $\leq 1^\circ$ with an accuracy of $1 \mu\text{rad}$ at distances of about 1 m [3]. Currently, quasi-phase-matched interactions in periodically polarized inverted crystals with counterpropagating waves are being intensively studied [6-8].

In [9-10], for increasing the efficiency of the signal of the anti-Stokes component of SRS, the authors propose to vary the nonlinear cubic susceptibility in layered media. In this case, the layers contain Raman active nonlinear media and passive media without nonlinearity. In [11], it was experimentally obtained that such a passive layer can be obtained using such a nonlinear effect as the optical Stark effect. The authors of [11] experimentally found that by applying such a nonlinear effect as the optical Stark effect, one could obtain a similar passive layer. The shift of levels in the field of a light wave leads to a shift in the spectral scattering lines. Excitation by laser fields leads to a significant shift of the scattering component. Obtaining such a displacement in a constant electric field requires high intensities of the order of breakdown values and higher. Hence, the action of the electric field of laser radiation with a strength sufficient for the spectral shift leads to the absence of amplification of Stokes radiation in this layer. The so-called passive layers are implemented using this fact. In [9-10], the authors use a numerical method for studying

the quasiphase matching interaction in such a layered Raman-active medium using the first-order Euler method. In the works [12-16] authors theoretically studied quasi-phase matching interactions in periodic nonlinear structures.

The authors analyze the frequency transformations in the constant field approximation (CFA) or by numerical methods. In CFA, the amplitude and phase of the pump radiation are constant, and the coherent length of the nonlinear medium depends solely on the detuning of the wave vectors. However, this simplification is valid only at the beginning of the interaction, when the effect of the excited wave on the pump wave is small and pump depletion ignored. As a result, we do not consider a few features of the nonlinear process. A direct numerical calculation of the coupled equations for each layer is possible. However, the use of the analytical method makes it possible to obtain the optimal parameters of the problem from specific analytical expressions and give recommendations for achieving maximum conversion efficiency. Therefore, it is expedient to use the constant intensity approximation (CIA), which considers the back reaction of the excited wave to the pump wave [17]. In this approximation, the coherent length, in addition to the detuning of the interacting waves, depends on such parameters of the problem as the intensities of the main radiation, Stokes (anti-Stokes) component and losses in the medium. In this approximation we considered second harmonic generation, sum frequency generation, third harmonic generation in regular domain structures (RDS), and intracavity conversion from which we will cite one of these works, for example [18]. In addition, we considered spontaneous Raman scattering of the Stokes and anti-Stokes components at intracavity transformation [19] and at CARS in optic fiber [20]. In this work, to calculate the parameters of quasi-phase-matched generation of the anti-Stokes component of SRS in a layered structure, we use this analytical method. Frequency conversion processes in a layered structure consisting of periods of a "lattice" of modulation of the nonlinear susceptibility are considered. Moreover, the values of the complex amplitudes of the pump radiation and the scattering components at the output of each layer are the input values of the corresponding complex amplitudes for the next layer. We obtained analytical expressions for the conversion efficiency to the anti-Stokes component and analyzed the factors that limit the efficiency of the frequency conversion process.

2 Theory

Let us consider the quasi-phase matching interaction of waves at the generation of the anti-Stokes SRS component in a medium with a periodic structure. The structure consists of a few successive layers with periodically changing values of the cubic susceptibility. We carry out the analytical analysis according to the procedure we used in [18].

To study these processes, it is necessary to solve truncated equations that describe the process of generation of the anti-Stokes SRS component in each of the layers separately. At all stages, the problem is solved with the appropriate boundary conditions, namely, the output parameters of the previous layer are the input parameters of the next layer. Let us consider SRS of the Stokes and anti-Stokes components under the action of a laser pump wave in the first layer with a Raman active medium with cubic susceptibility $\chi^{(3)}$. To describe these processes in the quasi-stationary case, the system of wave equations has the form [4, 21]:

$$\begin{aligned}\frac{dA_p}{dz} + \delta_p A_p &= -i[\gamma_p^s |A_s|^2 A_p + \gamma_p^{sa} A_p^* A_s A_a e^{-i\Delta z} + \gamma_p^a |A_a|^2 A_p], \\ \frac{dA_s}{dz} + \delta_s A_s &= -i[\gamma_s |A_p|^2 A_s + \gamma_s^{sa} A_p^2 A_a^* e^{i\Delta z}], \\ \frac{dA_a}{dz} + \delta_a A_a &= -i[\gamma_a |A_p|^2 A_a + \gamma_a^{sa} A_p^2 A_s^* e^{i\Delta z}],\end{aligned}\quad (1)$$

where

$$\begin{aligned}\gamma_p^s &= \frac{2\pi\omega_p}{cn_p} \chi_s^{(3)*}(\omega_p = \omega_s - \omega_a + \omega_p), \\ \gamma_p^{sa} &= \frac{2\pi\omega_p}{cn_p} [\chi_{sa}^{(3)*}(\omega_p = \omega_a + \omega_s - \omega_p) + \chi_{sa}^{(3)*}], \\ \gamma_p^a &= \frac{2\pi\omega_p}{cn_p} \chi_a^{(3)}(\omega_p = \omega_a - \omega_a + \omega_p), \\ \gamma_s &= \frac{2\pi\omega_s}{cn_s} \chi_s^{(3)}(\omega_s = \omega_p - \omega_p + \omega_s), \\ \gamma_s^{sa} &= \frac{2\pi\omega_s}{cn_s} \chi_{sa}^{(3)}(\omega_s = 2\omega_p - \omega_a), \\ \gamma_a &= \frac{2\pi\omega_a}{cn_a} \chi_a^{(3)}(\omega_a = \omega_p - \omega_p + \omega_a), \\ \gamma_a^{sa} &= \frac{2\pi\omega_a}{cn_a} \chi_{sa}^{(3)*}(\omega_a = 2\omega_p - \omega_s).\end{aligned}$$

Here, $A_{p,s,a}$ the complex amplitudes of the pump wave, the Stokes and anti-Stokes components at frequencies $\omega_{p,s,a}$, γ_i ($i = s, a$), $\gamma_p^{s,a}$ are the nonlinear coupling coefficients at SRS of the Stokes and anti-Stokes components, $\gamma_{p,s,a}^{sa}$ anti-Stokes components, $\delta_{p,s,a}$ and $n_{p,s,a}$ determine the linear losses and refractive indices at the corresponding frequencies $\omega_{p,s,a}$. $\Delta = 2k_p - k_s - k_a$ denotes the phase mismatch of the wave vectors, the waves propagate in the positive direction of the z axis.

In the general case, the cubic susceptibility contains resonant and nonresonant parts. However, for most purely Raman media [21-22], the actual nonresonant electronic susceptibility is small compared to the resonant part, so we do not take it into account in our calculations below. We carry out the consideration for the case of exact frequency resonance when the cubic susceptibility $\chi_{p,s,a}^{(3)}$.

We consider the generation of the anti-Stokes scattering component at SRS considering the losses of all interacting waves in the general case, when both the pump wave and the Stokes component wave are present at the input to the first layer of length l_1 . Then the boundary conditions at the input have the form:

$$A_{p,s}(z=0) = A_{p0,so} \exp(i\varphi_{p0,so}), \quad A_a(z=0) = 0, \quad (2)$$

where $z=0$ corresponds to the input to the first layer and $\varphi_{p0,so}$ are the initial values of the phase of the pump wave and the Stokes component at the input to the first layer.

Solving system (1) in CIA, i.e. $I_p(z=0) = I_{p0}$, $I_s(z=0) = I_{s0}$, considering (2), for the complex amplitude of the anti-Stokes component at the output of the first layer, we obtain

$$A_a(z=l_1) = -i\gamma_a^{sa} A_{p0}^2 A_{s0}^* \frac{\sin \lambda_1^a l_1}{\lambda_1^a} \cdot \exp \left[-\frac{\delta_a + \delta_s + 2\delta_p + i(\gamma_1^a - \lambda)}{2} l_1 + i(2\varphi_{p0} - \varphi_{s0}) \right], \quad (3)$$

where

$$\gamma_1^a = 2\gamma_p^s I_{s0} + \gamma_a I_{p0} - \gamma_s^* I_{p0} \cdot I_j = A_j \cdot A_j^*,$$

$$\lambda_1^a = \sqrt{\gamma_a^{sa} I_{p0} (2\gamma_p^{sa} I_{s0} - \gamma_s^{sa} I_{p0}) - \frac{[\delta_a \cdot \delta_s - 2\delta_p + i(\gamma_a I_{p0} + \gamma_s^* I_{p0} - 2\gamma_p^s I_{s0} + \Delta)]^2}{4}}.$$

Under the conditions $(\gamma_a + \gamma_s^*) I_{p0} = 2\gamma_p^s I_{s0}$ and $\delta_s + 2\delta_p = \delta_a$ we get $\lambda_1^a = \sqrt{\frac{\Delta^2}{4} - \Gamma_a^2}$, $\Gamma_a^2 = \gamma_a^{sa} I_{p0} (\gamma_s^{sa} I_{p0} - 2\gamma_p^{sa} I_{s0})$, $l_{1,coh}^{CIA} = 0.5\pi / \sqrt{\frac{\Delta^2}{4} - \Gamma_a^2}$. And in the case of CFA ($\gamma_p^{sa} = 0$, $\gamma_p^{s,a} = 0$, $\gamma_s = 0$), a similar expression is $\lambda_1^{CFA} = \Delta/2$ and $l_{1,coh}^{CFA} = \pi/\Delta$. Let us compare the expressions for coherent lengths in both approximations. In CIA, the coherent length and phase of the anti-Stokes wave depend, in addition to the phase mismatch Δ , on the intensities of the pump and Stokes waves.

Neglecting losses, from (3) we obtain

$$A_a(z=l_1) = -i\gamma_a^{sa} A_{p0}^2 A_{s0}^* \frac{\sinh \lambda_1^{a''} l_1}{\lambda_1^{a''}} \cdot \exp \left[-i\frac{\gamma_1^a - \mathcal{A}}{2} l_1 + i(2\varphi_{p0} - \varphi_{s0}) \right], \quad (4)$$

where

$$\lambda_1^{a''} = \sqrt{\frac{[(\gamma_a I_{p0} + \gamma_s^* I_{p0} - 2\gamma_p^s I_{s0} + \Delta)]^2}{4} + \Gamma_a^2}.$$

From (4) one can obtain an expression for the intensity $I_a(l_1)$.

Now we use the analysis applied above for the anti-Stokes component for the case of the Stokes scattering component. To do this, we will solve system (1) with respect to the complex amplitude of the Stokes component in CIA, i.e., at the input $I_p(z=0) = I_{p0}$, $I_a(z=0) = I_{a0} = 0$. Considering the boundary conditions (2), at the output of the first layer, we obtain ($\delta_{p,s,a} = 0$)

$$A_s(z=l_1) = A_{s0} \left[\cos \lambda_1^s l_1 - i \left(\gamma_s A_{p0}^2 \exp(i2\varphi_{p0}) - \frac{\gamma_1^s - \Delta}{2} \right) \frac{\sin \lambda_1^s l_1}{\lambda_1^s} \right] \cdot \exp \left(i\varphi_{s0} - i\frac{\gamma_1^s - \Delta}{2} l_1 \right) \quad (5)$$

$$\lambda_1^s = \sqrt{\gamma_s^{sa} \gamma_a^{sa} I_{p0}^2 - \frac{(\gamma_s I_{p0} + \gamma_a^* I_{p0} - 2\gamma_p^s I_{s0} + \Delta)^2}{4}}, \quad \gamma_1^s = 2\gamma_p^s I_{s0} + \gamma_s I_{p0} - \gamma_a^* I_{p0}.$$

From (5) one can obtain an expression for the intensity $I_s(l_1)$. It follows from (5) that with increasing pump power, the maximum conversion to the Stokes component occurs at shorter coherent lengths. From (5) one can also find the optimal value of the pump intensity or obtaining the maximum signal of the Stokes component.

In further analytical expressions, we do not consider wave losses in order to avoid cumbersome formulas. Substituting (4) into the third equation of system (1), for the complex amplitude of the pump wave at the exit from the first layer, we obtain

$$A_p^2(l_1) = \left\{ \frac{A_{s0}^2 A_{p0}^2}{A_s^*(l_1)} \left[\cos \lambda_1^a l_1 - i \frac{(\gamma_1^a - \Delta)}{2} \frac{\sin \lambda_1^a l_1}{\lambda_1^a} \right] \right. \\ \left. \times \exp \left[i(2\varphi_{p0} - \varphi_{s0}) - i\frac{\gamma_1^a - \Delta}{2} l_1 \right] + i \frac{\gamma_a}{\gamma_s^{sa}} \frac{A_a(l_1)}{A_s^*(l_1)} I_{p0} \right\} \times \exp(-i\Delta l_1) \quad (6)$$

Let us calculate the phases of the pump wave and the anti-Stokes component in the first layer. In system (1), we make a change: $A_j(z) = a_j(z) \cdot \exp(i\varphi_j z)$, $j = p, s, a$. Applying the standard procedure used in [23], we obtain the phase of the pump wave in CIA:

$$\varphi_p(z) = \varphi_{p0} + \gamma_p^{sa} \gamma_a^{sa} I_{p0} I_{s0} \left(\gamma_a I_{p0} + \frac{\Delta - \gamma_1^a}{2} \right) \frac{z}{2\lambda_1^{a2}} [1 - \text{sinc}(2\lambda_1^a z)] - \gamma_p^s I_{s0} z, \quad (7)$$

For comparison, in the CFA $\varphi_p(z) = \text{const.}$, since in this approximation the phase of the pump wave is constant.

Similarly, for the anti-Stokes component, we obtain an expression for the phase:

$$\varphi_a(z) = (\Delta - \gamma_1^a)z/2 - \pi/2 + 2\varphi_{p0} - \varphi_{s0}. \quad (8)$$

Now consider the behavior of complex amplitudes $A_{p,s,a}$ in the second layer, which has no non-linearity (therefore, this layer is passive). In this case, the initial values of the complex wave amplitudes are determined by their values at the end of the first layer from expressions (3) and (4), i.e. boundary conditions have the form:

$$A_{p,s,a}(z=l_1) = A_{p,s,a}(l_1) \exp[i\varphi_{p,s,a}(l_1)]. \quad (9)$$

Here $\varphi_{p,s,a}(l_1)$ are the changes in the phase of the waves at the transition from the first layer to the second at frequencies $\omega_{p,s,a}$, respectively, $z = 0$ again corresponds to the input, but already $l_1 = l_{1,coh}^{CIA}$

Since the absorption of waves is not considered, when passing through the second layer (passive), in which $\chi_{s,a,sa}^{(3)} = 0$, we have at the output of the second layer of length l_2 :

$$\begin{aligned} A_p(z = l_2) &= A_p(l_1) \exp[i\varphi_p(l_1) + i\varphi_p(l_2)], \\ A_s(z = l_2) &= A_s(l_1) \exp[i\varphi_s(l_1) + i\varphi_s(l_2)], \\ A_a(z = l_2) &= A_a(l_1) \exp[i\varphi_a(l_1) + i\varphi_a(l_2)]. \end{aligned} \quad (10)$$

It should be noted that in RDS with quadratic and cubic nonlinearity, the quasi-phase matching condition (i.e., compensation of the phase mismatch between interacting waves) was satisfied by changing the sign of the nonlinear polarization for neighboring layers-domains. Analytically, this was considered by changing the sign of the nonlinear coefficients when passing from layer to layer, which is equivalent to changing the generalized phase by an amount equal to π .

In the case under study, the phase mismatch of waves equal to π , which occurs in a Ramanactive medium, is compensated in the second passive layer. Compensation is due to the optical Stark effect. It also provides a change in the generalized phase waves in the passive layer (ψ_2) by π [9], i.e., one can write:

$$\psi_2 = 2\varphi_p(l_2) - \varphi_a(l_2) - \varphi_s(l_2) = \pi.$$

Thus, the quasi-phase-matching condition is satisfied in the passive layer. Therefore, all three waves will enter the third layer without phase mismatch. Hence, in this layer, the intensity of the anti-Stokes component further increases up to the coherent length of the third layer. In terms of energy, this leads to further energy transfer from the pump wave and the Stokes component to the anti-Stokes component.

Consider the behavior of complex amplitudes $A_{p,s,a}$ in the third layer, which is nonlinear. In this case, the initial values of the complex wave amplitudes at the input to the third layer are equal to their output values at the end of the second layer, i.e. conditions (8)–(10). The boundary conditions have the form:

$$A_p(z = 0) = A_p(l_2), \quad A_s(z = 0) = A_s(l_2), \quad A_a(z = 0) = A_a(l_2). \quad (11)$$

Here $z = 0$ again corresponds to the entrance, but already in the third layer.

The behavior of complex amplitudes in this case is also described by system (1), however, the corresponding nonlinear coupling coefficients and the phase mismatch of the waves in the third layer will be denoted by dashes. In CIA, solving system (1) considering the boundary conditions (11), for the complex amplitude of the anti-Stokes component at the output of the third layer, $z = l_3$, we obtain:

$$\begin{aligned} A_a(l_3) &= A_a(l_2) \left\{ \cos \lambda_3^a l_3 + \left[\frac{\gamma_a^{sa'}}{\gamma_a^{sa}} \left(\lambda_1^a \cot \lambda_1^a l_1 + \gamma_a I_{po} + i \frac{\Delta - \gamma_1^a}{2} \right) e^{i\psi} - i \left(\gamma_3 + \frac{\Delta'}{2} \right) \right] \frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right\} \\ &\times \exp \left[i\varphi_a(l_2) - i \frac{\gamma_3^a - \Delta'}{2} l_3 \right], \end{aligned} \quad (12)$$

where

$$\begin{aligned} \gamma_3 &= \frac{\gamma_a^{sa'} + \gamma_s^{s'}}{2} I_p(l_1) - \gamma_p^s I_s(l_1), \\ \lambda_3^a &= \sqrt{\frac{\gamma_a^{sa'} I_p(l_1) [2\gamma_p^{sa} I_s(l_1) - \gamma_s^{sa} I_p(l_1)] + (\gamma_a I_p(l_1) + \gamma_s^s I_p(l_1) - 2\gamma_p^s I_s(l_1) + \Delta)^2}{4}}, \end{aligned}$$

Here, $\psi = \psi_1 + \psi_2$, where $\psi_1 = 2\varphi_p(l_1) - \varphi_a(l_1) - \varphi_s(l_1) - \Delta l_1$ is the generalized phase of the waves during the passage of the first layer.

$$I_a(l_3) = I_a(l_2) \left[\left(\cos \lambda_3^a l_3 + c \frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right)^2 + \left(b \frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right)^2 \right], \quad (13)$$

where

$$\begin{aligned} c &= \frac{\gamma_a^{sa'}}{\gamma_a^{sa}} \left[(\lambda_1^a \cot \lambda_1^a l_1 + \gamma_a I_{po}) \cos \psi + \frac{\gamma_1^a - \Delta}{2} \sin \psi \right], \\ b &= \frac{\gamma_a^{sa'}}{\gamma_a^{sa}} \left[(\lambda_1^a \cot \lambda_1^a l_1 + \gamma_a I_{po}) \sin \psi - \frac{\gamma_1^a - \Delta}{2} \cos \psi \right] - \left(\gamma_3 + \frac{\Delta'}{2} \right). \end{aligned}$$

It can be seen from expression (13) that the terms with l_1 enter $I_a(l_2)$ and into the expressions for the coefficients c and b (through $I_a(l_1)$). This leads to a change in the coherent length of the first layer for obtaining the maximum signal of the anti-Stokes component after three layers.

At $\lambda_1 l_{1,coh}^{CIA} = \pi/2$ the intensity $I_a(l_3)$ is equal to

$$I_a(l_3) = I_a(l_2) \times \left\{ \left[\cos \lambda_3^a l_3 \pm \frac{\gamma_a^{sa'}}{\gamma_a^{sa}} \gamma_a I_{po} \frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right]^2 + \left[\left(\pm \frac{\Delta - \gamma_1^a}{2} \cdot \left(\frac{\gamma_a^{sa'}}{\gamma_a^{sa}} \right) - \gamma_3 - \frac{\Delta'}{2} \right) \right]^2 \left(\frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right)^2 \right\} \quad (14)$$

The upper sign corresponds to the case $\psi = 2\pi n$, and the lower sign corresponds to $\psi = (2n+1)\pi$, $n = \pm 1, \pm 2, \dots$. Let us assume that the same nonlinear media are used in the first and third active layer, then for $\gamma_a^{sa} = \gamma_a^{sa'}$ we obtain:

$$I_a(l_3) = I_a(l_2) \left[\left(\cos \lambda_3^a l_3 \pm \gamma_a I_{po} \frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right)^2 + \left(\pm \frac{\Delta - \gamma_1^a}{2} - \frac{\Delta'}{2} - \gamma_3 \right)^2 \left(\frac{\sin \lambda_3^a l_3}{\lambda_3^a} \right)^2 \right]. \quad (15)$$

It follows from (15) that for an increase in the output intensity $I_a(l_3)$ at a constant phase mismatch ($\Delta = \Delta$) the case is favorable when the terms in brackets with the phase mismatch contribute of the same sign to $I_a(l_3)$ and thereby ensure its increase. This condition is observed at $\psi = \pi(2n + 1)$. This conclusion also follows from Fig. 1 - 4 obtained by numerical calculation of the analytical expression (15) in CIA.

Note that the coherent lengths of the active layers and depend not only on the value of the phase mismatch, but also on the intensities of the pump wave and the Stokes component. Moreover, these parameters refer not only to the current third active layer ($\Delta', I_p(l_1), I_s(l_1)$), but also to the first active layer ($\Delta, I_{po,so}$).

3 Results and discussion

All graphical results obtained based on analytical formulas in the CIA are calculated for the parameters of a specific experiment [9-10] for compressed hydrogen. The article provides not just one numerical estimate of the conversion efficiency in the CIA for the parameters of a particular experiment using the obtained analytical formulas, but entire graphical dependences of the expected behavior of the conversion efficiency on various experimental parameters with specific recommendations for the optimal values of the problem parameters: coherent length, period of the phase matching curve etc. From (4), (5), (7), (8) and (15) obtained analytically in CIA, one can numerically analyze the behavior of the intensities and phases of the anti-Stokes and Stokes scattering components in a three-layer structure. In this case, we choose the parameters of the problem from existing experiments [9-10]. We choose the most active Raman medium as the active medium: compressed hydrogen (having a maximum combination shift at SRS among gases, equal to 4155 cm^{-1}). The second harmonic Nd:YAG (532 nm) was used as the pump wave. The wavelength of the Stokes (682.8 nm) and anti-Stokes components (435.69 nm) of SRS was determined from the frequency shift. These wavelengths are necessary when calculating the nonlinear coefficients of the scattering components. The pump intensity varied from tens of MW/cm^2 to tens of GW/cm^2 . The phase mismatch Δ varied in the range of $2\text{--}15 \text{ cm}^{-1}$ and the SRS gain for compressed H_2 varied in the range of $1\text{--}10 \text{ cm/GW}$.

The results of the numerical calculation of the corresponding expressions are presented in Figures 1–4. The curves are plotted for the case of identical phase mismatch values in each of the active layers ($\Delta = \Delta'$), optimal layer lengths, which are determined from the conditions $\lambda_{1,3}^a = \pi/2$ and in the absence of losses.

Figure 1 shows the dependences of the intensities of the scattering components in the first layer $I_a(l_1)$, using (4), and $I_s(l_1)$, using (5), for different values of the phase mismatch and input values of the intensity of the Stokes component I_{so} . In this case, the behavior of the dependence $I_a(l_1)$ with a phase mismatch is determined by the term $\frac{\sinh \lambda_1^{a''} l_1}{\lambda_1^{a''}}$, which through the parameter $\lambda_1^{a''}$ depends on Δ (curves 3 and 4). Similarly, from (5) the behavior of the curves for the Stokes component is determined. The dependence $I_s(l_1)$ on the phase mismatch is contributed by term $\frac{\lambda_1^s - \Delta}{2}$ the sine and cosine functions through the parameter λ_1^s . This explains the observed weak response $I_a(l_1)$ to the same change in the phase mismatch (curves 3 and 4) compared to $I_s(l_1)$ (curves 1 and 2). In addition, a change in the phase mismatch leads to a shift of the oscillations $I_s(l_1)$ along the longitudinal coordinate z (curves 1 and 2). However, at different I_{so} (curves 3, 5, and 6), the period of oscillations practically does not change, which, as the analysis showed, relates to the smallness of the contribution of the term with I_{so} .

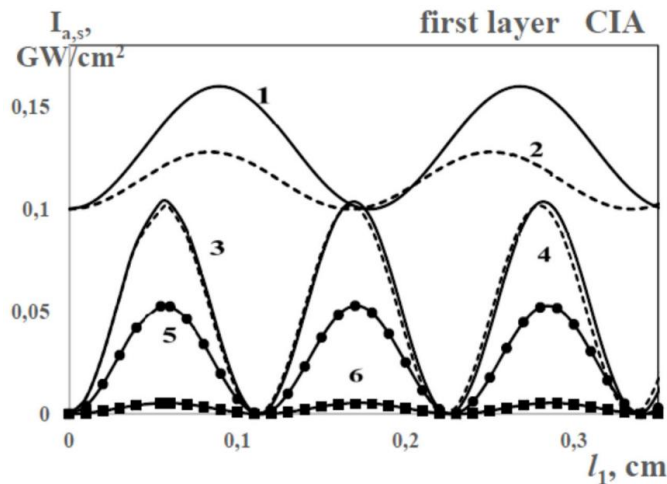


Figure 1. Dependences of the intensities of the scattering components in the first layer $I_a(l_1)$ (curves 3–6) and $I_s(l_1)$ (curves 1–2) for $I_{po} = 10 \text{ GW/cm}^2$, $I_{ao} = 0$ at $\Delta = 13 \text{ cm}^{-1}$ (curves 2 and 4) and 15 cm^{-1} (curves 1, 3, 5, 6) and $I_{so} = 10^{-2} I_{po}$ (curves 1–4), $5 \cdot 10^{-3} I_{po}$ (curve 5), $5 \cdot 10^{-4} I_{po}$ (curve 6). We calculated the dependencies in CIA.

Figure 2, according to (7) and (8), shows the dynamics of the behavior of the phases of the pump wave and the anti-Stokes component as it moves along the z axis, calculated using (7) and (8). Intersection of lines indicates the optimal value of the length of the nonlinear medium (the coherent length), at which the maximum transfer of the energy of the exciting waves into the energy of the generated anti-Stokes wave occurs.

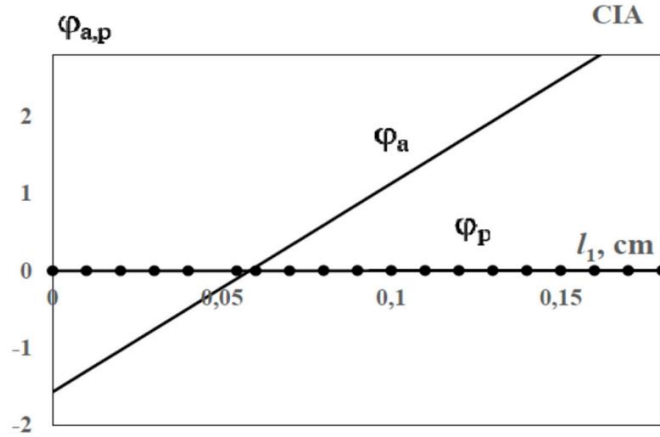


Figure 2. Dependences of the phases of the pump wave $\varphi_p(l_1)$ and the anti-Stokes component $\varphi_a(l_1)$ in the first layer for $I_{p0} = 10 \text{ GW/cm}^2$, $I_{a0} = 0$, $I_{s0} = 10^{-2}I_{p0}$, $\Delta = 3.84 \text{ cm}^{-1}$. We calculated the dependences in CIA.

Figure 3 shows how, under conditions of quasi-phase matching, a gradual smooth increase in the intensity of the anti-Stokes component occurs in the first, using (4), and third, according to (15), active layers. In the second passive layer, the intensity does not change, a horizontal section is observed (see insert). As soon as the intensity maximum is reached in the first layer at the coherent length of the first layer $l_{1,\text{coh}}^{\text{CIA}} = 0.0544 \text{ cm}$, the second passive layer starts. In the third layer, the maximum intensity is reached at the coherent length of the third layer $l_{3,\text{coh}}^{\text{CIA}} = 0.038 \text{ cm}$. As can be seen from the comparison, the coherent lengths of the active layers decrease, which was also noted in [9-10]. This is the opposite of the result obtained in RDS [15]. This contradiction was explained by the authors of [6] with the non-multiplicity of the frequencies of the interacting waves. Note that the distance between the minima of the phase-matching curve in CIA, in contrast to CFA is not constant. This must be considered when calculating the phase matching width in similar layered structures.

From Fig. 3, it turns out that at coherent lengths of the first $l_{1,\text{coh}}^{\text{CIA}}$ and third active layers $l_{3,\text{coh}}^{\text{CIA}}$, the optimal phase relationship between the interacting waves and the optimal ratio I_{s0}/I_{p0} (see Figure 1) it is possible to increase the maximum conversion efficiency of the anti-Stokes component I_a/I_{p0} from 0.01 in the first active layer to 0.026 in second active layer (see Figure 3). Comparison with Fig. 3 in [9] shows that a similar result realized there approximately on the 26th layer. By calculating the optimal parameters for each specific case, it is possible to increase the conversion efficiency even with a smaller number of active layers. The above calculations in CIA for two active media, if necessary, can be continued and applied to n number of layers, how we did it in the case of sum frequency generation in RDS.

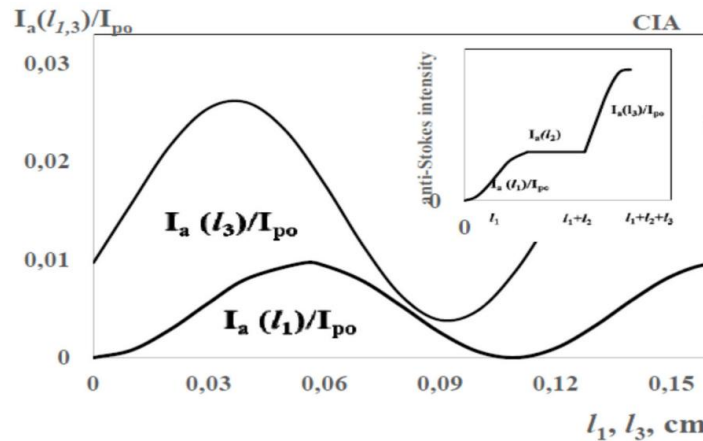


Figure 3. Dependences of the conversion efficiency of the anti-Stokes scattering component in the first $I_a(l_1)/I_{p0}$ and third layers $I_a(l_3)/I_{p0}$ for $I_{p0} = 10 \text{ GW/cm}^2$, $I_{a0} = 0$, $I_{s0} = 10^{-2}I_{p0}$ at $\Delta = 3.84 \text{ cm}^{-1}$, $l_{1,\text{coh}}^{\text{CIA}} = 0.0544 \text{ cm}$, $\psi = \pi(2n+1)$, $\psi_2 = \pi$. Insert: Dependency of $I_a(l_1, l_1 + l_2, l_1 + l_2 + l_3)/I_{p0}$. We calculated the dependences in CIA.

Figure 4, according to (15), shows the dependence of the intensity of the anti-Stokes component in the third layer on the layer length $I_a(l_3)$ at different pump intensities. There is an optimal value I_{p0} . For the given parameters of the problem $I_{p0}^{\text{opt}} = 9 \text{ GW/cm}^2$. With a change in the pump intensity, not only the intensity of the anti-Stokes component changes, but also the oscillation period, and we observed a shift of the minima. This is due to the $\lambda_{1,3}^a$ parameters associated with I_{p0} . This does not take place in the CFA.

Thus, for a specific experiment, using the analytical expressions obtained in the CIA one can calculate the optimal values of the problem parameters to achieve the maximum conversion to the anti-Stokes component at quasi-phase matching interaction, and consider the case of dissipative media.

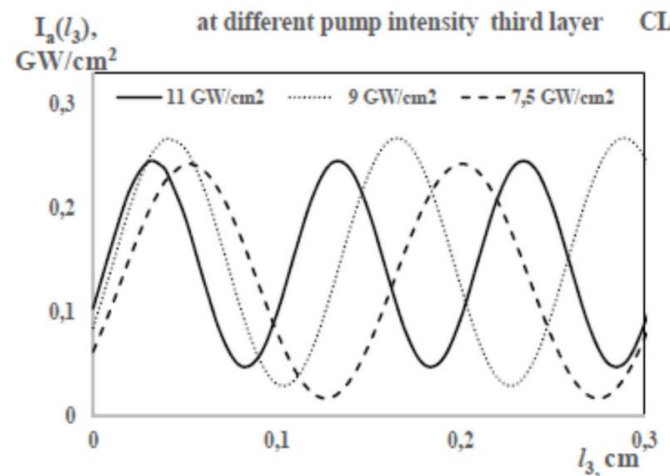


Figure 4. Dependence of the intensity of the anti-Stokes component in the third layer on the layer length $l_a(l_3)$ at $I_{p0} = 7.5 \text{ GW/cm}^2$ (dashed curve), 9 GW/cm^2 (dotted curve), and 11 GW/cm^2 (solid curve). We calculated the dependencies in CIA.

4 Conclusion

By calculating the optimal parameters of the problem (lengths of the active layers, phase detuning, pump and Stokes component intensities, optimal phase ratio), one can obtain high values of the conversion efficiency at the output of the layered structure even with a smaller number of active layers. Note that the coherent lengths of the active layers depend not only on the value of the phase mismatch, but also on the intensities of the pump wave and the Stokes component. Moreover, these parameters are not only for the current active layer, but also for the previous active layer. With a change in the pump intensity, not only the intensity of the anti-Stokes component changes, but also a period of oscillations, a shift of the minima occurs. Researchers need to consider this fact when calculating the phase matching width in layered structures. The dependence of the phase relations on the intensities of the interacting waves, considered in the CIA, is proof of a more correct study of the nonlinear interaction of optical waves in layered structures. There is no such dependence in the CFA.

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Foliar Application of Gehna Super Bio-stimulant Enhances Growth, Yield, and Nutrient Uptake in Maize (*Zea mays* L.) under South Indian Agroclimatic Conditions

CORRESPONDENCE → +



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ABSTRACT

Bio-stimulants represent a rapidly growing category of agronomic inputs that improve crop performance under both optimal and sub-optimal growing conditions. In this study, we evaluated the agronomic efficacy and economic viability of Gehna Super, a commercial plant bio-stimulant, applied as a foliar spray at four concentrations (2, 2.5, 3, and 5 ml L⁻¹ water) on maize (*Zea mays* L.) during Kharif 2022 at the University of Agricultural Sciences (UAS), GKVK, Bangalore. A randomized complete block design (RCBD) with five treatments replicated four times was employed. Gehna Super significantly enhanced plant height, leaf area index (LAI), total dry matter accumulation, cob length, kernel number, kernel yield, and N-P-K uptake compared to untreated control. Foliar spray at 5 ml L⁻¹ (T5) recorded the highest kernel yield (8,369 kg ha⁻¹; +36.9% over control) and total dry matter at harvest (463.16 g plant⁻¹). However, application at 3 ml L⁻¹ (T4) delivered the most favorable cost-benefit ratio (1:3.42). No phytotoxic effects were observed at any dose. Results indicate that Gehna Super at 2.5–3 ml L⁻¹ represents the optimal dose for maximizing economic returns in maize production under Eastern Dry Zone conditions of Karnataka, India.

Index Terms: bio-stimulant • Gehna Super • *Zea mays* • foliar spray • crop growth • kernel yield • nutrient uptake • cost-benefit ratio

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The author declares no conflict of interest.

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No generative AI was used for analysis or results.

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Foliar Application of Gehna Super Bio-stimulant Enhances Growth, Yield, and Nutrient Uptake in Maize (*Zea mays* L.) under South Indian Agroclimatic Conditions

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Abstract

Bio-stimulants represent a rapidly growing category of agronomic inputs that improve crop performance under both optimal and sub-optimal growing conditions. In this study, we evaluated the agronomic efficacy and economic viability of Gehna Super, a commercial plant bio-stimulant, applied as a foliar spray at four concentrations (2, 2.5, 3, and 5 ml L⁻¹ water) on maize (*Zea mays* L.) during Kharif 2022 at the University of Agricultural Sciences (UAS), GKVK, Bangalore. A randomized complete block design (RCBD) with five treatments replicated four times was employed. Gehna Super significantly enhanced plant height, leaf area index (LAI), total dry matter accumulation, cob length, kernel number, kernel yield, and N-P-K uptake compared to untreated control. Foliar spray at 5 ml L⁻¹ (T5) recorded the highest kernel yield (8,369 kg ha⁻¹; +36.9% over control) and total dry matter at harvest (463.16 g plant⁻¹). However, application at 3 ml L⁻¹ (T4) delivered the most favorable cost-benefit ratio (1:3.42). No phytotoxic effects were observed at any dose. Results indicate that Gehna Super at 2.5–3 ml L⁻¹ represents the optimal dose for maximizing economic returns in maize production under Eastern Dry Zone conditions of Karnataka, India.

Keywords: *bio-stimulant, Gehna Super, Zea mays, foliar spray, crop growth, kernel yield, nutrient uptake, cost-benefit ratio*

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1 Introduction

Maize (*Zea mays* L.) is the third most important cereal crop globally and the highest-yielding food grain crop in India, where it is grown across diverse agroclimatic zones on approximately 8.7 million hectares. In Karnataka, maize occupies a prominent position in the Kharif cropping system of the Eastern Dry Zone, a semi-arid agroclimatic region characterized by red sandy loam soils of low to medium fertility. Achieving sustainable yield improvement in this environment requires strategies that increase nutrient use efficiency, enhance canopy development, and strengthen reproductive performance without increasing the ecological footprint of production.

Plant bio-stimulants are defined by the European Biostimulant Industry Council as "substances or microorganisms that, when applied to plants or the rhizosphere, stimulate natural processes to enhance nutrient use efficiency, abiotic stress tolerance, quality traits, and/or availability of confined nutrients in the soil". These products include humic and fulvic acids, protein hydrolysates, seaweed extracts, and trace-element formulations. Their application as foliar sprays exploits the rapid uptake and systemic distribution of bioactive molecules through leaf stomata and cuticle, bypassing soil-mediated constraints such as nutrient fixation and microbial decomposition.

Gehna Super is a proprietary poly-nutrient, plant growth-promoting bio-stimulant manufactured by Meenakshi Agro Chemicals, Hyderabad, India. While several studies have documented yield benefits of generic bio-stimulants in cereals (Bulgari *et al.*, 2015; du Jardin, 2015; Van Oosten *et al.*, 2017), there is a paucity of replicated field data on the dose-response relationship of this formulation in maize under South Indian conditions. Establishing such evidence is critical for product registration, extension advisory, and farmer adoption.

The present investigation was therefore designed to: (i) assess the effect of Gehna Super at escalating concentrations on vegetative growth, dry matter accumulation, yield attributes, and grain yield of maize; (ii) quantify nutrient (N, P, K) uptake in response to bio-stimulant application; and (iii) determine the most economically viable application dose through cost-benefit analysis. We hypothesized that foliar application of Gehna Super would dose-dependently improve key agromorphological traits and that an intermediate concentration would optimize economic returns.

2 Materials and methods

2.1 Experimental Site and Soil characteristics

The field experiment was conducted during Kharif 2022 at the All India Coordinated Research Project (AICRP) on Sunflower, Zonal Agricultural Research Institute (ZARS), Gandhi Krishi Vigyan Kendra (GKVK), University of Agricultural Sciences (UAS), Bangalore. The site is located at 13°05' N latitude and 77°34' E longitude, at an altitude of 924 m above mean sea level, within Agroclimatic Zone V (Eastern Dry Zone) of Karnataka.

The soil was red sandy loam (Alfisol order) with the following physicochemical properties: coarse sand 53.4%, fine sand 14.8%, silt 16.6%, clay 15.2%; pH 5.89 (mildly acidic); electrical conductivity 0.35 dS m⁻¹; organic carbon 0.48%; available N 239.04 kg ha⁻¹ (low), available P 25.13 kg ha⁻¹ (medium), and available K 248.31 kg ha⁻¹ (medium). These characteristics are representative of rain-fed maize-growing soils in the Eastern Dry Zone.

2.2 Climatic conditions

The experimental site receives a mean annual rainfall of 1,328.4 mm, predominantly from June to November. During the cropping season (July–October 2022), total rainfall was 864.2 mm with a peak in October (361.0 mm). The mean maximum temperature ranged from 27.0 to 27.7 °C and mean minimum temperature from 16.9 to 18.7 °C. Maximum relative humidity ranged between 90 and 91%, and minimum relative humidity between 59 and 62%. These conditions provided adequate moisture for rainfed maize production without water-logging stress.

2.3 Experimental design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with five treatments replicated four times (20 plots total). Each plot measured 5.0 m × 5.0 m (25 m²), with 0.5 m buffer bunds between adjacent plots and 1.0 m alleyways between replications. Maize seeds (commercial variety) were sown on 15 July 2022 at a spacing of 50 cm × 30 cm using the dibbling method. The following treatments were evaluated:

T1: Untreated control (no bio-stimulant)

T2: Gehna Super foliar spray @ 2 ml L⁻¹ of water

T3: Gehna Super foliar spray @ 2.5 ml L⁻¹ of water

T4: Gehna Super foliar spray @ 3 ml L⁻¹ of water

T5: Gehna Super foliar spray @ 5 ml L⁻¹ of water

Foliar sprays were applied four times at 30, 45, 60, and 75 days after sowing (DAS) using a hand-operated knapsack sprayer with a flat-fan nozzle, ensuring uniform coverage of the crop canopy. The recommended dose of farm yard manure (FYM) was incorporated one week before sowing, and NPK fertilizers (DAP and muriate of potash) were applied as per crop requirements. Two hand weeding were performed at 15 and 30 DAS, followed by earthing-up at 30 DAS. Gap-filling was carried out two weeks after sowing to maintain optimum plant population.

2.4 Observations Recorded

Growth parameters. Ten randomly selected plants per plot were tagged for biometric measurements at 30, 45, 60, 75, and 90 DAS. Plant height was measured from the base to the tip of the newly emerged leaf using a measuring tape. Leaf count was performed manually. Leaf area per plant was measured using a leaf area meter; leaf area index (LAI) was computed as leaf area per plant divided by land area per plant (0.15 m²). Leaf, stem, and cob dry weights were determined after oven-drying at 65 °C to constant weight; total dry matter (TDM) was the sum of all components.

Yield and yield attributes. At harvest, ten randomly selected plants per plot were assessed for number of cobs per plant, cob length (cm), cob girth (cm), number of rows per cob, number of kernels per row, number of kernels per cob, kernel weight per cob (g), and test weight (100-kernel weight, g). Kernel yield and stover yield were measured plot-wise and converted to kg ha⁻¹. Harvest index (HI) was computed as kernel yield divided by total biological yield.

Nutrient uptake. Plant samples were digested in a di-acid mixture (HNO₃:HClO₄ = 9:4). Nitrogen content was determined by the micro-Kjeldahl method (Jackson, 1973); phosphorus by the vanadomolybdophosphoric acid colorimetric method at 660 nm; potassium by flame photometry. Nutrient uptake (kg ha⁻¹) was calculated as (nutrient content % × yield kg ha⁻¹) / 100.

Phytotoxicity. Phytotoxic symptoms (leaf injury, wilting, vein clearing, necrosis, chlorosis, stunting, epinasty, and hyponasty) were scored on a 0–10 scale at 3, 7, 10, and 14 days after each application (0 = no injury, 10 = 91–100% injury).

2.5 Statistical analysis

All data were subjected to Analysis of Variance (ANOVA) for RCBD using standard procedures (Cochran and Cox, 1957). Treatment differences were evaluated at $P \leq 0.05$ using the F-ratio test. Standard error of mean (S.E.m±) and critical difference (CD at 5%) were computed for each trait. Data requiring angular transformation (percentages) were transformed prior to analysis; untransformed means are presented in all tables. Statistical analyses were performed using GenStat software (VSN International, UK). All figures were prepared using Python 3.11 (matplotlib v3.8).

3 Results

3.1 Growth Parameters

3.1.1 Plant Height. Treatment had no significant effect on plant height at 30 DAS (pre-application baseline; Table 1), confirming homogeneous initial stand. After the commencement of foliar sprays, plant height diverged significantly among treatments at 45, 60, 75, and 90 DAS. The highest-dose treatment, T5 (5 ml L⁻¹), produced the tallest plants at all post-application stages (83.14, 151.46, 234.76, and 265.28 cm at 45, 60, 75, and 90 DAS, respectively) and exceeded the untreated control (T1: 68.08, 125.33, 194.27, and 219.52 cm) by 22.1%, 20.9%, 20.8%, and 20.8%, respectively. T5 was statistically at par with T4 (3 ml L⁻¹) and T3 (2.5 ml L⁻¹) throughout (Figure 1). These results indicate that Gehna Super

exerts a dose-dependent promotive effect on internode elongation and overall shoot extension, consistent with the role of cytokinin-like and auxin-potentiating compounds frequently reported in seaweed-based bio-stimulants (Battacharyya *et al.*, 2015).

Table 1. Effect of foliar spray of Gehna Super on plant height (cm) of maize at different growth stages

Treatment	30 DAS	45 DAS	60 DAS	75 DAS	90 DAS
T1: Untreated control	23.60	68.08	125.33	194.27	219.52
T2: Gehna Super @ 2 ml L ⁻¹	22.00	73.78	136.84	212.10	239.68
T3: Gehna Super @ 2.5 ml L ⁻¹	24.35	77.54	139.33	215.96	244.03
T4: Gehna Super @ 3 ml L ⁻¹	20.15	80.15	146.79	227.53	257.11
T5: Gehna Super @ 5 ml L ⁻¹	22.40	83.14	151.46	234.76	265.28
S.Em±	0.91	2.04	4.49	6.72	7.55
CD @ 5%	NS	6.29	13.82	20.70	23.26

NS = Non-significant; DAS = Days after sowing. Values are means of four replications. CD values at $P \leq 0.05$.

Figure 1. Effect of Gehna Super bio-stimulant on plant height of maize at different growth stages

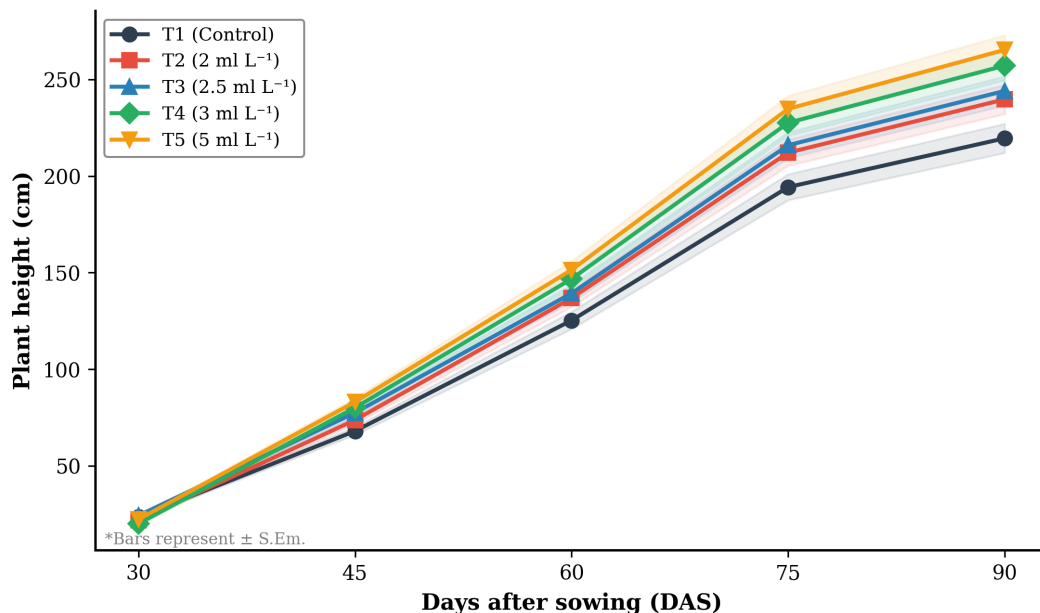


Figure 1. Effect of Gehna Super bio-stimulant on plant height of maize at different growth stages. Lines represent treatment means; shaded bands indicate $\pm$ S.E.m.

3.1.2 Number of Leaves per Plant. The number of leaves per plant did not differ significantly among treatments at 30 DAS. Significant differences emerged at 45 DAS and persisted through 90 DAS. T5 recorded the highest leaf number at 90 DAS (15.58 leaves plant⁻¹), exceeding T1 (13.75) by 13.3% and exceeding the CD value (1.25). T4 (14.60) and T3 (14.18) were intermediate and significantly superior to T1. Increased leaf number reflects enhanced meristematic activity and accelerated phyllochron development, likely mediated by cytokinin-type signals present in the bio-stimulant formulation.

3.1.3 Leaf area per Plant and Leaf area Index. Leaf area per plant was not significantly different at 30 DAS but diverged significantly from 45 DAS onwards. At 90 DAS, T5 attained the largest leaf area per plant (6,996.00 cm² plant⁻¹) compared to T1 (6,119.50 cm² plant⁻¹), representing a 14.3% increase. T4 (6,743.25 cm²) and T3 (6,561.25 cm²) were statistically on par with T5. Correspondingly, LAI at 90 DAS was highest in T5 (3.89) versus T1 (3.40), with T4 (3.75) and T3 (3.65) being at par (Figure 2). An LAI in the range of 3.5–4.0 is considered near-optimal for light interception in maize (Maddonni and Otegui, 1996), indicating that T3–T5 achieved a near-optimum canopy architecture.

Figure 2. Effect of Gehna Super bio-stimulant on Leaf Area Index of maize at different growth stages

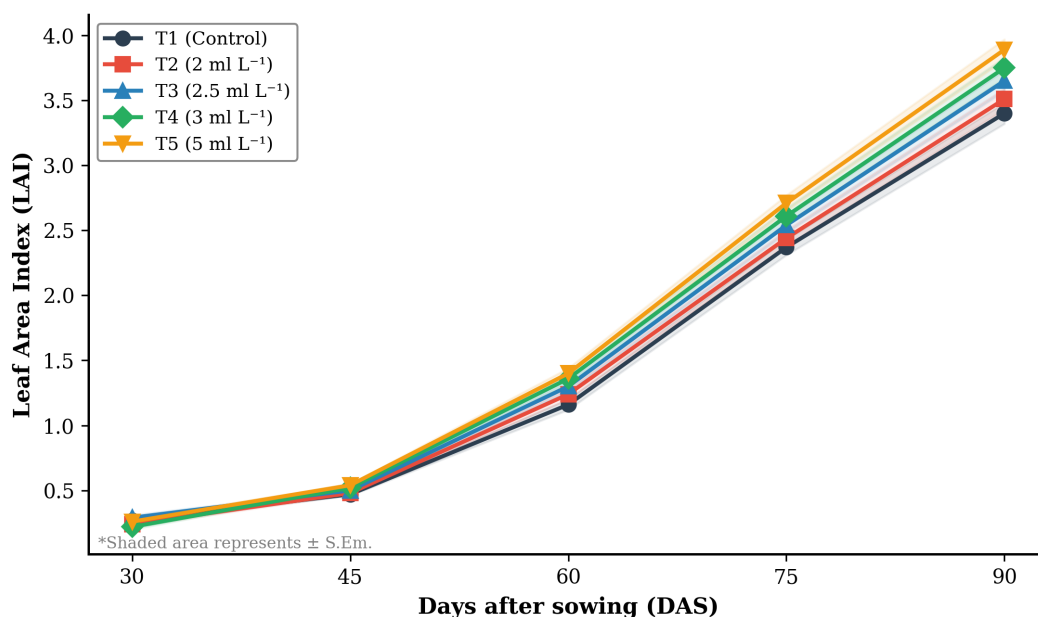


Figure 2. Effect of Gehna Super bio-stimulant on Leaf Area Index (LAI) of maize at different growth stages. Shaded bands indicate $\pm$ S.E.m.

3.1.4 Dry Matter Accumulation. Total dry matter (TDM) did not differ significantly at 30 DAS among treatments. Following bio-stimulant application, TDM increased significantly across all growth stages. At harvest, TDM was highest in T5 (463.16 g plant⁻¹), followed by T4 (433.77 g), T3 (400.05 g), T2 (409.52 g), and T1 (367.60 g; Figure 3). The increments over control were 25.6% (T5) and 18.0% (T4), reflecting the bio-stimulant's capacity to sustain source activity through the grain-filling phase. Component analysis revealed that cob dry matter exhibited the most pronounced response: T5 recorded 286.60 g cob dry matter plant⁻¹ at harvest versus 220.10 g in T1 (+30.2%), indicating preferential enhancement of assimilate partitioning to reproductive organs.

Figure 3. Effect of Gehna Super bio-stimulant on total dry matter accumulation of maize at different growth stages

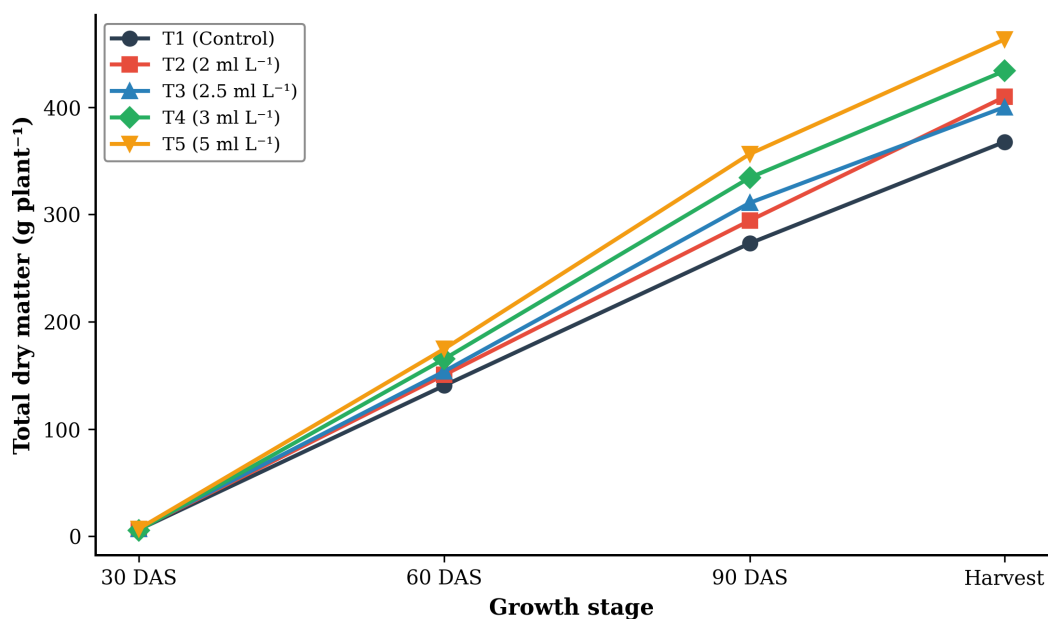


Figure 3. Effect of Gehna Super bio-stimulant on total dry matter accumulation (g plant⁻¹) of maize at different growth stages

Table 2. Effect of foliar spray of Gehna Super on yield attributes of maize at harvest

Treatment	Cobs plant ⁻¹	Cob length (cm)	Cob girth (cm)	Rows cob ⁻¹	Kernels row ⁻¹	Kernels cob ⁻¹	Kernel wt./cob (g)	Test wt. (g)
T1: Control	0.95	18.23	17.53	13.30	29.20	387.89	210.93	28.30
T2: 2 ml L ⁻¹	1.00	19.40	17.60	13.53	30.93	418.11	222.25	28.53
T3: 2.5 ml L ⁻¹	1.00	20.45	18.05	14.00	33.20	465.50	233.33	29.85
T4: 3 ml L ⁻¹	1.13	21.60	18.40	14.93	35.03	523.40	245.05	29.93
T5: 5 ml L ⁻¹	1.23	22.93	19.93	15.80	36.90	582.59	255.23	30.60
S.Em±	0.10	0.89	0.54	0.58	1.23	25.81	7.84	0.25
CD @ 5%	NS	2.73	1.65	1.77	3.78	79.52	24.17	0.78

NS = Non-significant. Values are means of four replications. CD at $P \leq 0.05$.

3.2 Yield Attributes

Yield-attributing traits were significantly influenced by treatments, except number of cobs per plant (Table 2). The highest-performing treatment, T5, recorded the greatest values for all significant yield components: cob length 22.93 cm (+25.8% over T1), cob girth 19.93 cm (+13.7%), rows per cob 15.80 (+18.8%), kernels per row 36.90 (+26.4%), kernels per cob 582.59 (+50.2%), kernel weight per cob 255.23 g (+21.0%), and test weight 30.60 g (+8.1%; Figure 6). T4 (3 ml L⁻¹) and T5 were statistically at par for most attributes, while T3 was intermediate. The marked increase in kernels per cob is agronomically noteworthy as it is a composite function of rows per cob and kernels per row, both of which are strongly sink-determined traits positively regulated by assimilate supply and pollination efficiency.

Figure 6. Effect of Gehna Super bio-stimulant on key yield attributes of maize at harvest

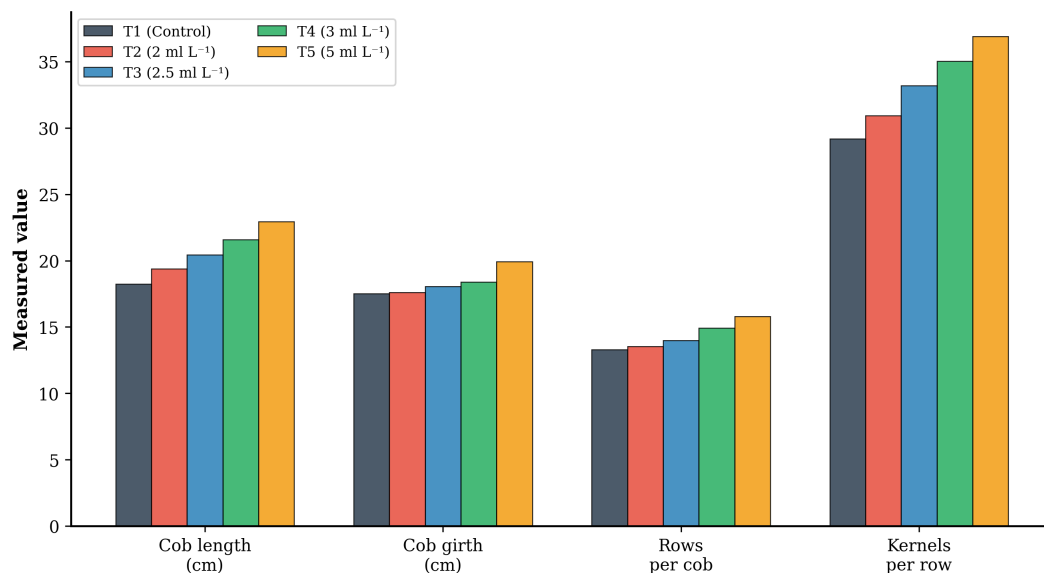


Figure 6. Effect of Gehna Super bio-stimulant on key yield attributes (cob length, cob girth, rows per cob, kernels per row) of maize at harvest.

3.3 Kernel Yield, Stover Yield, and Harvest Index

Kernel yield and stover yield differed significantly among treatments, whereas harvest index (HI) showed no significant treatment effect (Table 3). T5 produced the highest kernel yield (8,369 kg ha⁻¹), exceeding T1 (6,113 kg ha⁻¹) by 36.9%, T4 by 5.6%, and T3 by 9.9%. T4 and T3 were statistically on par with T5 (CD = 781 kg ha⁻¹). Stover yield followed a similar trend, with T5 recording 8,333 kg ha⁻¹ vs. 6,892 kg ha⁻¹ in T1 (+20.9%). The marginal and non-significant HI differences (0.470 to 0.501) suggest that bio-stimulant application improved overall crop productivity proportionally rather than altering the fundamental assimilate partitioning ratio (Figure 4).

Table 3. Effect of foliar spray of Gehna Super on kernel yield, stover yield, and harvest index of maize

Treatment	Kernel yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	Harvest index	Yield gain over T1
T1: Untreated control	6113.25	6891.75	0.470	—
T2: Gehna Super @ 2 ml L ⁻¹	7348.50	7561.00	0.492	+20.2%
T3: Gehna Super @ 2.5 ml L ⁻¹	7613.00	7800.50	0.494	+24.5%
T4: Gehna Super @ 3 ml L ⁻¹	7923.75	8052.25	0.496	+29.6%
T5: Gehna Super @ 5 ml L ⁻¹	8369.00	8333.00	0.501	+36.9%
S.Em±	253.52	209.69	0.011	—
CD @ 5%	781.17	646.11	NS	—

NS = Non-significant. Values are means of four replications. CD at $P \leq 0.05$. Yield gain (%) calculated relative to T1.

Figure 4. Effect of Gehna Super bio-stimulant on kernel yield and stover yield of maize

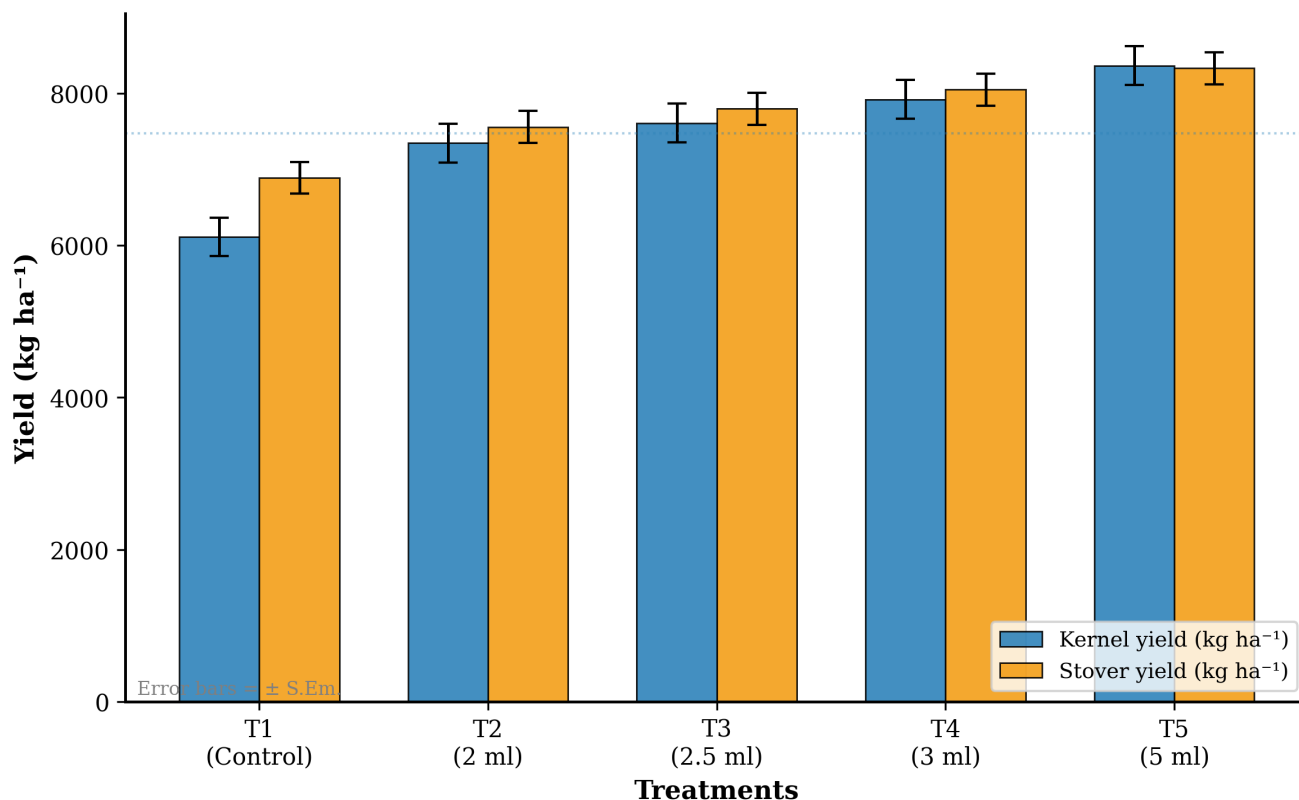


Figure 4. Effect of Gehna Super bio-stimulant on kernel yield and stover yield (kg ha⁻¹) of maize. Error bars represent $\pm$ S.E.m.

3.4 Nutrient Uptake

All three nutrients (N, P, K) showed significant treatment effects (Table 4; Figure 5). T5 recorded the highest N uptake (273.93 kg ha⁻¹), exceeding T1 (254.08 kg ha⁻¹) by 7.8%, while T4 (265.50 kg ha⁻¹) was statistically at par. Phosphorus uptake in T5 (50.98 kg ha⁻¹) exceeded T1 (45.48 kg ha⁻¹) by 12.1%. Potassium uptake in T5 (191.65 kg ha⁻¹) was 6.8% higher than T1 (179.48 kg ha⁻¹). The incremental improvements in nutrient uptake under Gehna Super treatments are attributable to expanded root systems and increased leaf area enabling greater photosynthetic carbon fixation, which in turn drives greater mineral absorption through mass flow and diffusion. The relatively modest percentage gains in nutrient uptake relative to the large percentage gains in yield suggest that bio-stimulant application improved nutrient use efficiency (NUE) — a highly desirable trait for sustainable intensification.

Table 4. Effect of foliar spray of Gehna Super on N, P, and K uptake (kg ha⁻¹) by maize

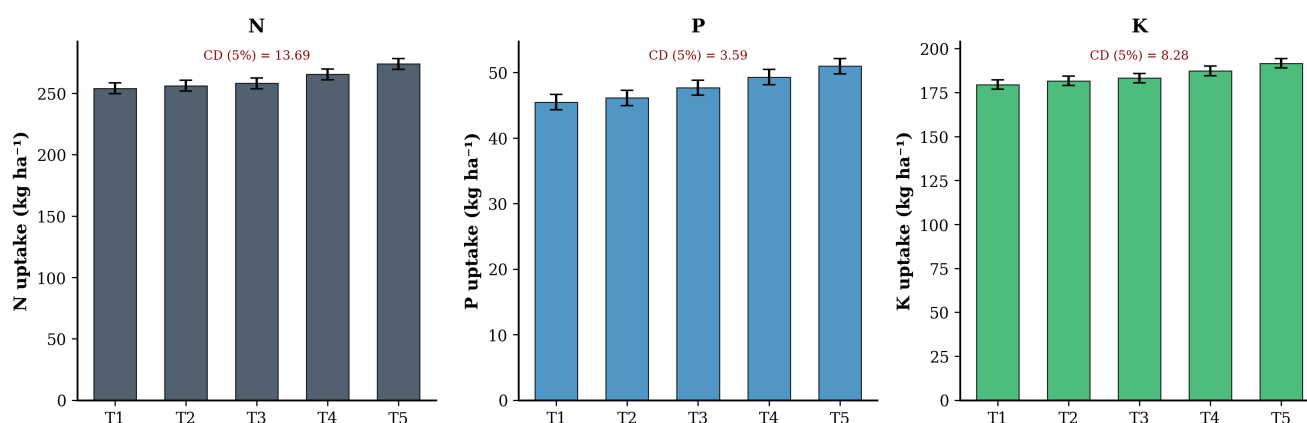
Treatment	N uptake (kg ha ⁻¹)	P uptake (kg ha ⁻¹)	K uptake (kg ha ⁻¹)
T1: Untreated control	254.08	45.48	179.48
T2: Gehna Super @ 2 ml L ⁻¹	256.20	46.13	181.63
T3: Gehna Super @ 2.5 ml L ⁻¹	258.13	47.68	183.18
T4: Gehna Super @ 3 ml L ⁻¹	265.50	49.30	187.33
T5: Gehna Super @ 5 ml L ⁻¹	273.93	50.98	191.65
S.E.m $\pm$	4.44	1.16	2.69
CD @ 5%	13.69	3.59	8.28

Values are means of four replications. CD at $P \leq 0.05$.

Table 5. Cost-benefit analysis of Gehna Super application on maize

Treatment	Market price (₹ L ⁻¹)	App. cost (₹ ha ⁻¹)	Kernel yield (kg ha ⁻¹)	Add. yield (kg ha ⁻¹)	Gross profit (₹ ha ⁻¹)	Net profit (₹ ha ⁻¹)	C:B ratio
T1: Control	—	—	6113.25	—	—	—	—
T2: 2 ml L ⁻¹	₹900	6800	7348.50	1235.25	25940	19140	1:2.81
T3: 2.5 ml L ⁻¹	₹900	7700	7613.00	1499.75	31495	23795	1:3.09
T4: 3 ml L ⁻¹	₹900	8600	7923.75	1810.50	38021	29421	1:3.42
T5: 5 ml L ⁻¹	₹900	12200	8369.00	2255.75	47371	35171	1:2.88

Application charges: ₹3,200 ha⁻¹; Market price of produce: ₹2,100 per quintal.

Figure 5. Effect of Gehna Super bio-stimulant on N, P, and K uptake by maize**Figure 5.** Effect of Gehna Super bio-stimulant on nitrogen (N), phosphorus (P), and potassium (K) uptake (kg ha⁻¹) by maize. Error bars represent ± S.E.m.

3.5 Phytotoxicity assessment

No phytotoxic symptoms — including leaf injury, wilting, vein clearing, necrosis, chlorosis, stunting, epinasty, or hyponasty — were observed at any application dose at any observation date (3, 7, 10, and 14 days after each spray). Phytotoxicity scores uniformly remained at zero (0 on the 0–10 scale) across all treatments, confirming the safety of Gehna Super for foliar application on maize up to 5 ml L⁻¹.

3.6 Cost-Benefit analysis

Cost-benefit analysis revealed that all Gehna Super treatments were economically profitable relative to no treatment (Table 5; Figure 7). T4 (3 ml L⁻¹) achieved the most favorable C:B ratio of 1:3.42, generating a net profit of ₹29,421 ha⁻¹ from an investment of ₹8,600 ha⁻¹. T3 (2.5 ml L⁻¹) and T5 (5 ml L⁻¹) yielded C:B ratios of 1:3.09 and 1:2.88, respectively. While T5 generated the highest absolute net profit (₹35,171 ha⁻¹), the disproportionately higher product cost at 5 ml L⁻¹ reduced its C:B ratio below that of T4. These findings underscore the economic advantage of using intermediate bio-stimulant doses for commercial maize production.

Figure 7. Cost-benefit ratio of Gehna Super bio-stimulant application on maize

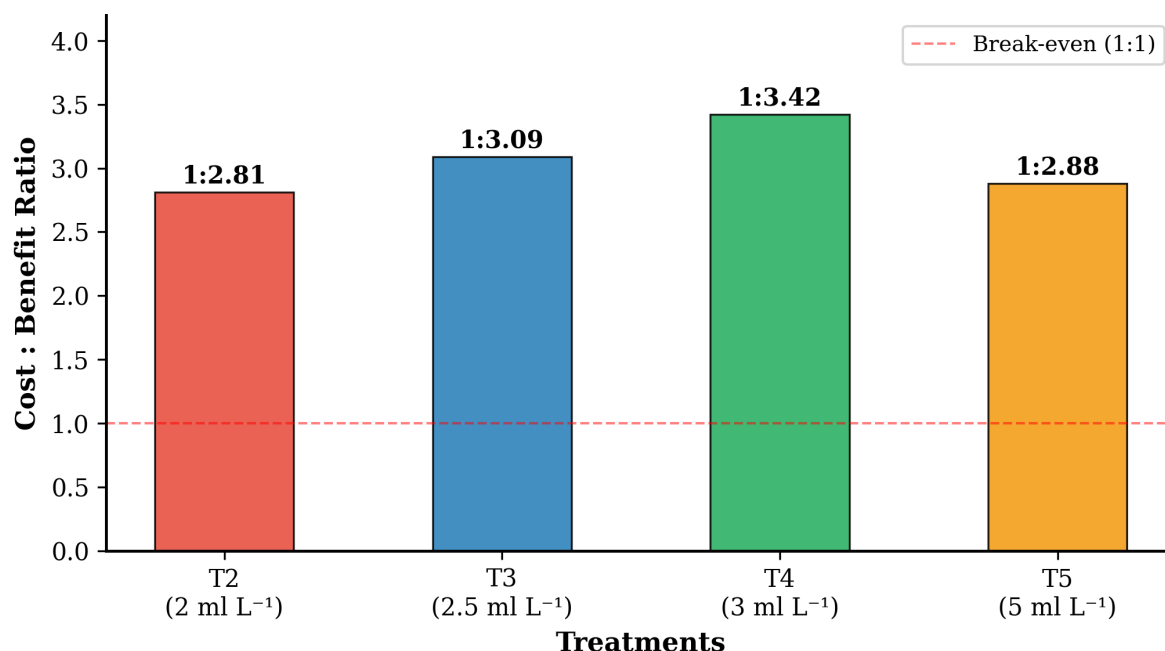


Figure 7. Cost-benefit ratio of Gehna Super bio-stimulant at different concentrations for maize production.

4 Discussion

The present study demonstrates a consistent, dose-dependent improvement in maize growth and productivity in response to foliar application of Gehna Super bio-stimulant. The progressive enhancement in plant height, LAI, dry matter accumulation, yield attributes, and kernel yield from T1 through T5 follows a classical dose-response pattern that is characteristic of bio-stimulant products containing bioactive molecules such as amino acids, trace elements, plant growth regulators, or polysaccharides. Although the precise composition of Gehna Super was not disclosed in this study, its agronomic effects align with those of protein hydrolysate- and seaweed-based bio-stimulants documented in the literature (Yakhin *et al.*, 2017; Rouphael and Colla, 2020).

The significant increases in plant height under bio-stimulant treatments are consistent with findings of Khan *et al.* (2020), who reported 15–25% height improvements in maize following seaweed extract application. The enhancement of LAI — a pivotal determinant of crop radiation interception and, consequently, dry matter production — is particularly significant. A higher LAI translates directly into greater canopy photosynthesis. The near-optimal LAI values (3.65–3.89) recorded in T3–T5 at 90 DAS are expected to support high biomass productivity, as confirmed by the TDM data.

The 50.2% increase in kernels per cob in T5 relative to T1 merits attention. Kernels per cob in maize is primarily determined during the period around silking when competition between ear growth and vegetative organs for assimilates is intense. Bio-stimulants have been shown to reduce this competition by enhancing phloem loading efficiency and ear sink strength (Ruzicka *et al.*, 2010). The concurrent improvements in cob length and girth further confirm that Gehna Super promotes ear development both in the linear (rachis elongation) and radial (cob filling) dimensions.

The modest but statistically significant improvements in N, P, and K uptake — combined with substantially larger yield gains — suggest improved NUE. This is consistent with the hypothesis that bio-stimulants activate root enzymatic processes (e.g., nitrate reductase, acid phosphatase) that improve ion acquisition per unit root biomass (Ruzicka *et al.*, 2010; Bulgari *et al.*, 2015). Under the low-to-medium fertility conditions of this Alfisol, even marginal improvements in NUE could translate into economically meaningful yield gains — a particularly valuable property for smallholder farming systems.

The C:B ratio analysis provides crucial practical guidance. The highest productivity (T5) does not translate into the best economic outcome because product cost scales with dose. The optimal economic dose of 3 ml L⁻¹ (T4) maximizes the C:B ratio at 1:3.42, meaning that every rupee invested in bio-stimulant application generates ₹3.42 in returns. This finding is directly actionable for extension advisory and farmer decision-making.

The complete absence of phytotoxicity across all doses and all observation points is an important safety confirmation for product registration and commercial use. This is consistent with the regulatory classification of bio-stimulants as low-risk inputs compared to conventional pesticides or high-nitrogen fertilizers.

5 Conclusion

This study provides the first replicated, multi-dose field evidence for the agronomic efficacy of Gehna Super bio-stimulant in maize under South Indian Eastern Dry Zone conditions. Foliar application significantly enhanced vegetative growth (plant height, leaf area index, dry matter accumulation), yield attributes (cob dimensions, kernel number), and kernel yield (up to 36.9% over untreated control at 5 ml L⁻¹). Nutrient uptake

was improved, indicating enhanced nutrient use efficiency. Gehna Super was phytotoxically safe at all tested concentrations. The dose of 3 ml L⁻¹ applied four times (at 30, 45, 60, and 75 DAS) is recommended as the optimal agronomic and economic rate, yielding a C:B ratio of 1:3.42. Future research should investigate the molecular basis of Gehna Super's mode of action, its performance across maize hybrids and irrigation levels, and its integration with precision nutrient management for further productivity gains.

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Action and Entropy: Base Physical Quantities

CORRESPONDENCE



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ABSTRACT

Action, entropy, frequency, speed, electric charge are proposed as base physical quantities of a new system. Base quantities would be directly linked to fundamental constants of physics h , k_B , $\Delta \nu_{Cs^{133}}$, c , e . Each base quantity would be defined independently of the others.

Index Terms: Action • Entropy • base quantities • base units

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Luc R.M. Morin*



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RESEARCH ARTICLE

Action and Entropy: Base Physical Quantities

Luc R.M. Morin*

Abstract

Action, entropy, frequency, speed, electric charge are proposed as base physical quantities of a new system. Base quantities would be directly linked to fundamental constants of physics $h, k_B, \Delta\nu_{Cs}^{133}, c, e$. Each base quantity would be defined independently of the others.

Keywords: Action, Entropy, base quantities, base units

Correspondence: Luc R.M. Morin

1 Introduction

According to de Broglie, action and entropy are base physical quantities [1].

“As a man who has devoted his whole life to the study of matter... I can tell you as a result of my research about the atoms this much: there is no matter as such.” Such were the words Planck addressed to a conference in Florence in 1944 [2].

In 2018, 26th-CGPM [3] defined SI base units on a set of seven constants (figure 1) and redefined the mass unit, no longer by reference to the mass of a prototype, but by setting the value of ... Planck constant.

26th-CGPM [3] mass defining method, together with Planck and de Broglie thoughts, suggests to consider a new system in which *action* and *entropy* would be base physical quantities [8].

2 SI Historical

“The creation of the decimal metric system at the time of the French Revolution and the subsequent deposition of two platinum standards representing the metre and the kilogram, on 22 June 1799, in the Archives de la République in Paris, which can be seen as the first step that led to the present International System of Units.” [4]

In November 2018, the 26th CGPM [3] redefined *“the SI on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the seven base units are deduced”*.

Table 1 displays SI base physical quantities, SI base units and their SI symbols [5].

base quantity name	base quantity symbol	Base unit name	base unit symbol
time	t	second	s
length	l, x, r , etc.	metre	m
mass	m	kilogram	kg
electric current	I, i	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

Table 1. SI base Physical Quantities, base units and symbols [5]

Within SI system, frequency, electrical charge, speed and molar entropy are derived physical quantities. Table 2 shows their units, as functions of SI base units [6]. It is noticed that action is not mentioned as a derived quantity.

derived quantity	quantity symbol	unit name	unit symbol	unit in SI base units
frequency		hertz	Hz	s^{-1}
electric charge		coulomb	C	A s
speed, velocity	v			$m s^{-1}$
molar entropy				$kg m^2 s^{-2} mol^{-1} K^{-1}$

Table 2. SI derived Physical Quantities and SI derived units [6]. Blank boxes correspond to symbols or names that are not defined in BIPM 9th ed. [5]

Figure 1 shows SI links between fundamental constants of physics ($\Delta\nu_{Cs}$, c , h , e , k_B , N_A , K_{cd}) and SI base units [7].

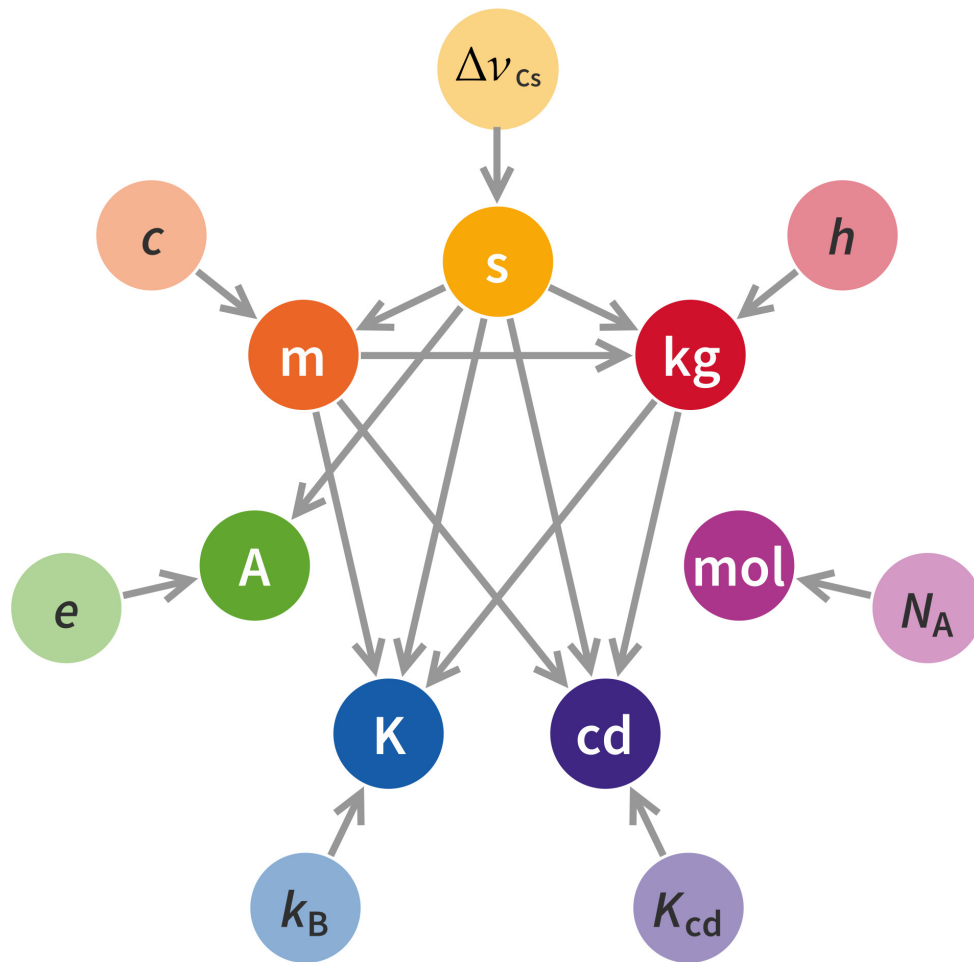


Figure 1. Links between fundamental constants of physics and SI base units [7].

3 New System: base quantities, units, symbols

Note: in present paper, the amount of substance and the luminous intensity are not studied. Only, action, entropy, frequency, speed and electric charge are studied here.

3.1 Proposed base physical quantities

26th CGPM [3] defining method, together with Planck and de Broglie thoughts, suggests that we should consider a new system of base physical quantities. In such a system, action, entropy, frequency, speed and electric charge would be base physical quantities.

Each of these physical quantities would be directly linked to fundamental constants of physics: Planck constant h , Boltzmann constant k_B , hyperfine transition frequency of the Caesium 133 atom $\Delta\nu_{Cs}^{133}$, speed of light in vacuum c and elementary charge e (figure 2).

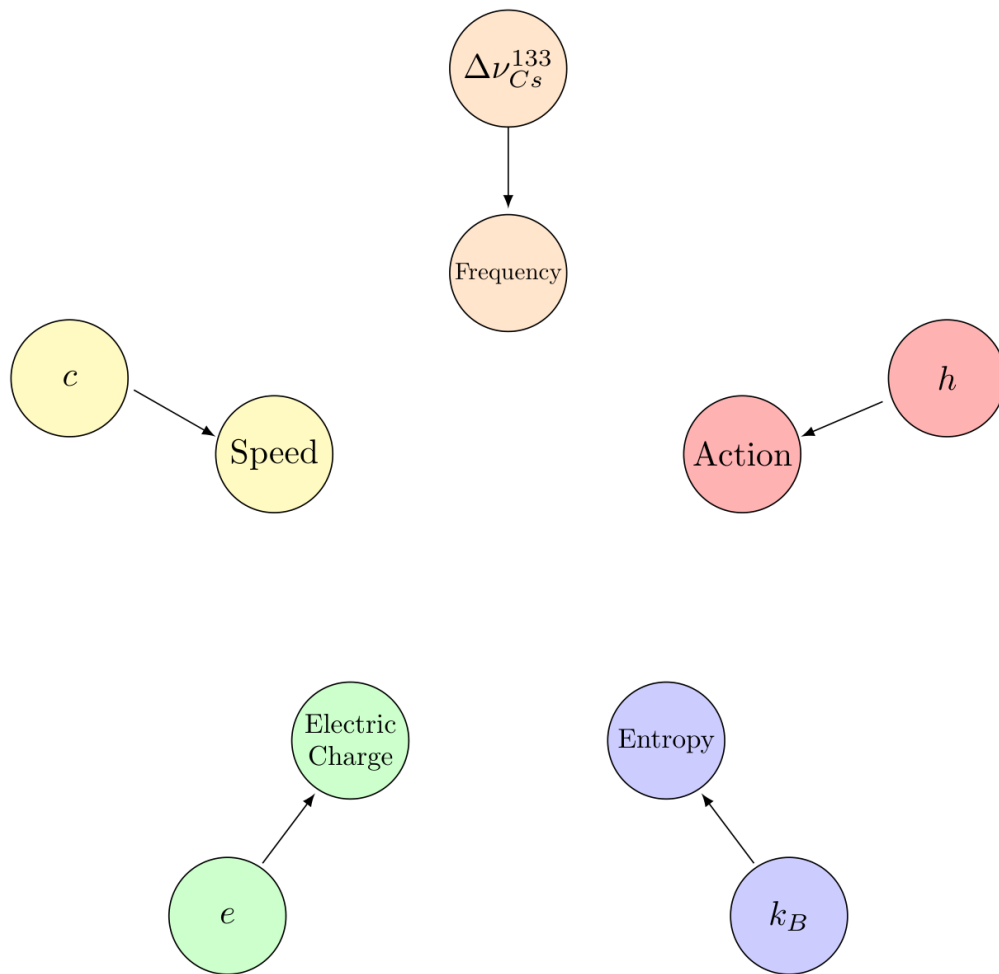


Figure 2. Links between fundamental constants of physics and proposed new system of base physical quantities.

3.2 Proposed quantities symbols

Table 3 shows the proposed base quantities names and the proposed base quantities symbols. It is proposed to use capital calligraphic fonts for base physical quantities of the new system $\mathcal{A}, \mathcal{S}, \mathcal{N}, \mathcal{V}, \mathcal{Q}$ (Table 3).

quantity name	quantity symbol
Action	$\mathcal{A}$
Entropy	$\mathcal{S}$
Frequency	$\mathcal{N}$
Speed	$\mathcal{V}$
Electric charge	$\mathcal{Q}$

Table 3. Base quantities: names and symbols - New system

3.3 Proposed unit names and unit symbols

Within the new system NS, each of the fundamental constants $h, k_B, \Delta\nu_{Cs}^{133}, c$ and e would be equal to one.

The proposed name of the unit of action is the planck, symbol Pk. One planck is the NS numerical value of the Planck constant, i.e., $h = 1$ Pk.

The proposed name of the unit of entropy is the boltzmann, symbol Bz. One boltzmann is the NS numerical value of the Boltzmann constant, $k_B = 1$ Bz.

The proposed name of the unit of frequency is the elementary frequency, symbol ν_{Cs} . One elementary frequency is the NS numerical value of the frequency of the unperturbed ground-state hyperfine transition of the Caesium 133 atom, i.e., $\Delta\nu_{Cs}^{133} = 1 \nu_{Cs}$.

The proposed name of the unit of speed is the light speed, symbol Ls¹. One light speed is the NS numerical value of speed of light in vacuum, $c = 1$ Ls.

¹Alternatively, it would be possible to name the unit of speed after Arago.

The proposed name of the unit of electric charge is the elementary electric charge, symbol Qe^2 . One elementary electric charge is the NS numerical value of the elementary charge, i.e., $e = 1 \text{ Qe}$.

Table 4 shows the proposed names of the NS base units and the proposed symbols of the NS base units. Table 5 shows the fundamental constants, their symbols and their new system numerical values.

unit name	unit symbol
planck	Pk
boltzmann	Bz
elementary frequency	ν_{Cs}
light speed	Ls
elementary electric charge	Qe

Table 4. Base units: names and symbols - New system

name	symbol	n value
Planck constant	h	1 Pk
Boltzmann constant	k_B	1 Bz
hyperfine transition Cs^{133}	$\Delta\nu_{\text{Cs}}^{133}$	1 ν_{Cs}
speed of light in vacuum	c	1 Ls
elementary charge	e	1 Qe

Table 5. Fundamental Constants within NS

Table 6 converts new system units to SI units. Table 7 converts SI units to new system units (NS). Table 8 summarises the NS base quantities and the related fundamental constants of physics.

Unit name	Unit value in SI
planck	1 Pk = $6.62607015 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1}$
boltzmann	1 Bz = $1.380649 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$
elementary frequency	1 ν_{Cs} = $9192631770 \text{ s}^{-1}$
light speed	1 Ls = $299792458 \text{ m s}^{-1}$
elementary electric charge	1 Qe = $1.602176634 \times 10^{-19} \text{ A s}$

Table 6. Units Conversion NS $\rightarrow$ SI

SI Unit	SI Unit in NS units
second	1 s = $9192631770 \nu_{\text{Cs}}^{-1}$
metre	1 m = $30.6633319 \text{ Ls } \nu_{\text{Cs}}^{-1}$
kilogram	1 kg = $1.4755214 \times 10^{40} \text{ Pk } \nu_{\text{Cs}} \text{ Ls}^{-2}$
ampere	1 A = $6.789687 \times 10^8 \text{ Qe } \nu_{\text{Cs}}$
kelvin	1 K = $2.2266653 \text{ Pk } \nu_{\text{Cs}} \text{ Bz}^{-1}$

Table 7. Units Conversion SI $\rightarrow$ NS

Quantity name	Quantity symbol	Unit name	Unit symbol	Unit value
Action	$\mathcal{A}$	planck	Pk	1 Pk = h
Entropy	$\mathcal{S}$	boltzmann	Bz	1 Bz = k_B
Frequency	$\mathcal{N}$	elementary frequency	ν_{Cs}	1 ν_{Cs} = $\Delta\nu_{\text{Cs}}^{133}$
Speed	$\mathcal{V}$	light speed	Ls	1 Ls = c
Electric charge	$\mathcal{Q}$	elementary electric charge	Qe	1 Qe = e

Table 8. Summary of proposed new system base quantities and related fundamental constants of physics

3.4 Conversion of dimensions of base quantities NS $\leftrightarrow$ SI

According to the new system, time, length, mass, temperature and electric current would not be base physical quantities but NS derived physical quantities.

Table 9 shows proposed symbols for the dimensions of NS base quantities. Table 10 converts the new system dimensions to the SI dimensions. Table 11 converts the SI dimensions to the new system dimensions.

²Alternatively, it would be possible to name the unit of electric charge after Stoney.

Base quantity	Symbol for dimension
Action	A
Entropy	S
Frequency	N
Speed	V
Electric Charge	Q

Table 9. Symbols for dimensions of NS base quantities

Base quantity	Quantity dimension (NS)	Quantity dimension (SI)
Action	A	$L^2 M^1 T^{-1}$
Entropy	S	$L^2 M^1 T^{-2} \Theta^{-1}$
Frequency	N	T^{-1}
Speed	V	$L^1 T^{-1}$
Electric Charge	Q	$I^1 T^1$

Table 10. Dimension conversion NS $\rightarrow$ SI

Base quantity	Quantity dimension (SI)	Quantity dimension (NS)
time	T	N^{-1}
length	L	VN^{-1}
mass	M	ANV^{-2}
electric current	I	QN
temperature	Θ	ANS^{-1}

Table 11. Dimension conversion SI $\rightarrow$ NS

4 Discussion

What is studied here is not only a matter of units, but mainly a matter of physical quantities. Several points must be stressed:

4.1 Definition of base physical quantities

Figure 1 shows how the SI base physical quantities are entangled. Here, each base quantity is defined independently of the others. Figure 3 shows the proposed new system of base quantities: each base quantity would be defined by reference to only one physical constant.

4.2 Action and Entropy

Physical quantity action is not mentioned in BIPM reports as a base quantity, nor as a derived quantity. Here, following de Broglie [1], action and entropy would be considered as base physical quantities.

4.3 Temperature

The treatment of temperature is modified. Within the SI, temperature is a base physical quantity. Within the new system, temperature is not a base quantity, but a quantity derived from the NS base physical quantities action, frequency and entropy. Temperature is homogeneous to action $\times$ frequency $\times$ (entropy) $^{-1}$.

4.4 Mass

The treatment of mass is modified. Within the SI, mass is a base physical quantity. Within the new system, mass is not a base quantity, but a quantity derived from the NS base physical quantities action, frequency and speed. Mass is homogeneous to action $\times$ frequency $\times$ (speed) $^{-2}$.

4.5 Definition of units of action and entropy

As action is considered a base physical quantity, it is necessary to define a unit of action. The proposed name of the unit of action is the planck, symbol Pk. One planck is the NS numerical value of the Planck constant, i.e., $h = 1$ Pk.

As entropy is considered a base physical quantity, it is necessary to define a unit of entropy. The proposed name of the unit of entropy is the boltzmann, symbol Bz. One boltzmann is the NS numerical value of the Boltzmann constant, i.e., $k_B = 1$ Bz.

4.6 Comparison with BIPM reports

BIPM [5] establishes the international system of **units**, which is based on seven defining constants, drawn from the fundamental constants of physics.

Appendix 3 of the 26th CGPM [3] defined the kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\,649 \times 10^{-23}$ when expressed in the unit $J\,K^{-1}$, which is equal to $kg\,m^2\,s^{-2}\,K^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{Cs}$. This definition of the kelvin is based on four constants k_B , h , c and $\Delta\nu_{Cs}^{133}$.

The same remark applies to:

- the kilogram which is defined by reference to three constants h , c and $\Delta\nu_{Cs}^{133}$

- the metre, which is defined by reference to two constants $\Delta\nu_{Cs}^{133}$ and c
- the ampere, which is defined by reference to two constants e and $\Delta\nu_{Cs}^{133}$.

Only the second is defined independently of the other units.

Present paper proposes a system of five base physical quantities: action, entropy, frequency, speed and electric charge. These quantities are related to fundamental physical constants: h , k_B , $\Delta\nu_{Cs}^{133}$, c and e .

Each base physical quantity of the new system is defined independently of the others. Table 12 summarises physical quantities and defining constants according to BIPM [5] from one part and physical quantities and defining constants according to the proposed new system from the other part.

BIPM [5]		Proposed new system	
Physical Quantity	Defining constants	Physical Quantity	Defining constant
time	$\Delta\nu_{Cs}^{133}$	frequency	$\Delta\nu_{Cs}^{133}$
length	$\Delta\nu_{Cs}^{133}, c$	speed	c
electric current	$\Delta\nu_{Cs}^{133}, e$	electric charge	e
mass	$\Delta\nu_{Cs}^{133}, c, h$	action	h
temperature	$\Delta\nu_{Cs}^{133}, c, h, k_B$	entropy	k_B

Table 12. Physical quantities and defining constants according to BIPM [5] and to proposed new system

5 Conclusion

Action and entropy are considered as base physical quantities. Mass and temperature are considered as derived physical quantities. Figure 3 summarises the links between the proposed new system of base quantities, the fundamental constants and the proposed units. Each base quantity of the new system is defined independently of the others (Table 12, Figure 3).

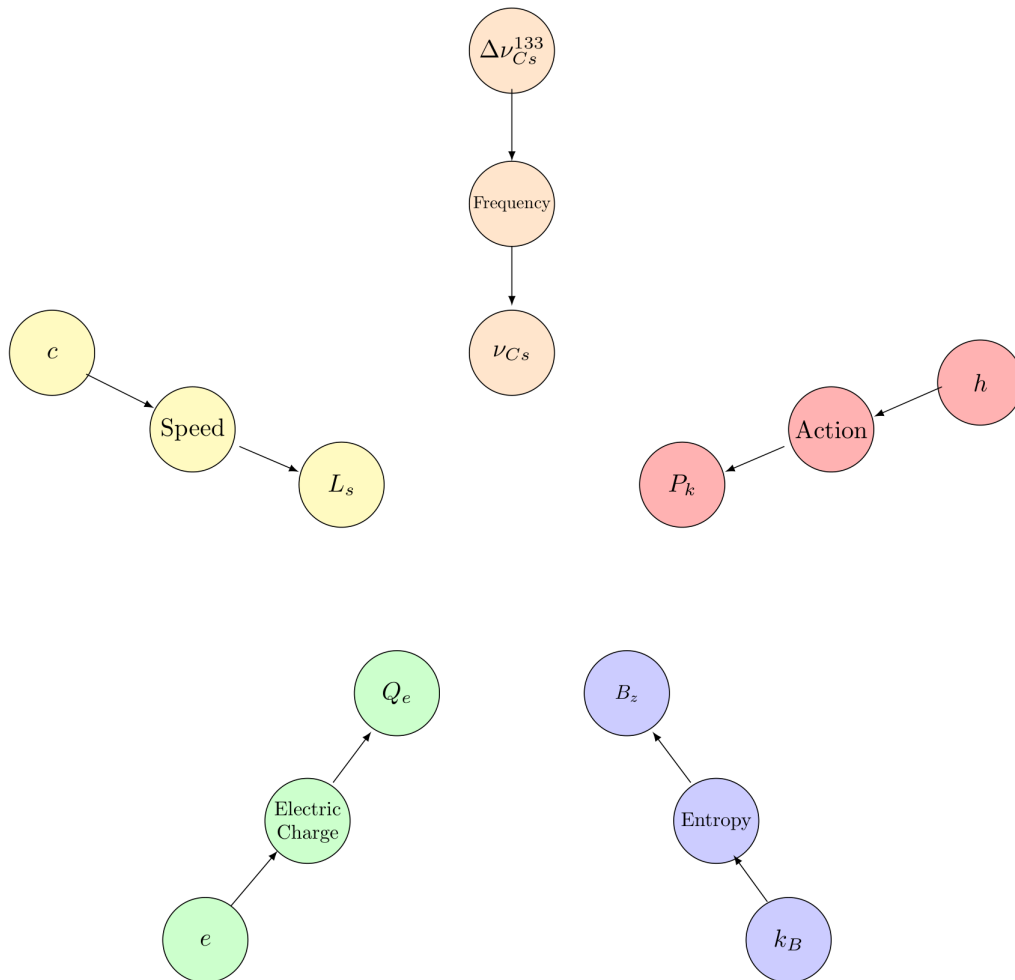


Figure 3. New system of base quantities, fundamental constants, units.

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Research Index

Technical concepts and key subjects are indexed at their verified discussion pages.

KEY SUBJECTS Acid Mine Drainage • Action • AI Ethics • Bio-Stimulant • Constant Intensity Approximation • Arrow of Time • Arsenic Removal • Entropy

A		
Acid Mine Drainage	1	
Action	7–8, 16, 20–21, 24–25, 40–46	
Action and Entropy	41, 45–46	
Advantages of Nanotechnology	2	
AI Ethics	7, 19, 21	
Anti-Stokes Component	24–30	
Anti-Stokes Generation	24	
Arrow of Time	7–9, 11–12, 21	
Arsenic Removal	1–4	
B		
Base Physical Quantities	41–46	
Base Quantities	41–46	
Base Quantity	41, 45–46	
Base Units	41–42, 44	
Bio-Stimulant	32–39	
Biomolecular Condensation as Coordination Percolation	17	
Boltzmann Constant	42–45	
C		
Cancer as Frayed Coordination	17	
Chemical Extraction	4	
Classical Limit	10	
Climate Governance	7, 16, 20–21	
Climatic Conditions	33	
Coherent Length	25–29	
Collective Action	7, 16, 20–21	
Comparison with BIPM Reports	45	
Complex Amplitudes	24–27	
Connection to Holographic and Entropic Gravity	9	
Constant Intensity Approximation	24–25, 31	
Conversion Efficiency	24–25, 28–30	
Coordination Density	9–11, 15–20	
Coordination Density and Emergent Geometry	9	
Coordination Dynamics	9–12, 14, 16, 19, 21	
Coordination Ontology	7, 14, 16, 19–21	
Cosmological and Astrophysical Paradoxes	13	
Cosmological Consequences	7, 10	
Cost–Benefit Analysis	32, 38	
Cost–Benefit Ratio	32, 39	
D		
Dark Sector	7, 10, 20–21	
Definition of Base Physical Quantities	45	
Definition of Units of Action and Entropy	45	
Derived Physical Quantities	41, 44, 46	
Distributed Temperature Sensor	24	
also: DTS		
Dry Matter Accumulation	32, 35, 39	
E		
Early Structure Anomalies	17	
Electric Charge	41–46	
Emergent Spacetime	7, 22	
Empirical Predictions and Falsifiability	11	
Entanglement and the Epr Paradox	12	
Entropy	7, 9, 13, 16, 41–46	
Evolutionary Dynamics as Coordination Percolation	18	
Execution, Interaction	7–9, 21	
Experimental Design and Treatments	33	
Experimental Site and Soil Characteristics	33	
F		
Factors Influencing NP Performance	2	
Farm Yard Manure	33	
also: FYM		
Field Equations of Coordination	9	
Foliar Spray	32–34, 36–37	
Free Will	15, 22	
Fundamental Constants	13, 41–46	
Fundamental Constants of Physics	41–45	
Fundamental Physical Constants	46	
G		
Gandhi Krishi Vigyan Kendra	32–33, 40	
also: GKVK		
Gehna Super	32–40	
Gehna Super Bio-Stimulant	32, 34–39	
Growth Parameters	33	
H		
Harvest Index	33, 36	
also: HI		
Hematite Nanoparticles	1–3	
HMNPs	1–4	
Hubble Tension	7, 16	
Hume’s Problem of Induction	15	
Hybrid Approach for Arsenic Remediation	1	
Hydrogen	1, 3, 24, 28, 30	
I		
Inductively Coupled Plasma Mass Spectrometry	1, 3	
also: ICP-MS		
Instrumental Neutron Activation Analysis	1, 3	
also: INAA		
Irreversibility as Structural Non-Commutativity	8	
K		
Kernel Yield	32–33, 36–39	
Kernel Yield, Stover Yield, and Harvest Index	36	
Kernels Per	33, 36, 39	
L		
Leaf Area Index	32–35, 39	
also: LAI		
Legacy Survey of Space and Time	16–17, 21	
also: LSST		
M		
Mass	1, 4, 11, 18, 20, 37, 41, 44–47	
Material and Methods	3	
Materials and Methods	33	
Mathematical and Computational Paradoxes	14	
Metric as Derivative	9	
Mining Waste Management	1	
Mining Waste Treatment and Metal Extraction	3	
N		
Nanoscale Iron Oxides	2	
Neural Coordination and Neurodegenerative Disease	17	
Number of Leaves Per Plant	34	
Nutrient Uptake	32–33, 37, 39	
O		
Observations Recorded	33	
Olbers’ Paradox	13	
P		
P Vs Np	14, 20	
Part II	7–8, 12, 16, 20	
Particle Size	1–4	
Percolation Threshold	7, 10–11, 13, 17, 19	
Phase Mismatch	25–28, 30	
Philosophical Implications	11	
Philosophical Paradoxes	15	
Phytotoxicity Assessment	38	
Planck Constant	41–45	
Plant Height	32–34, 39	
Primitive Operations	8	
Process Philosophy	7, 9	
Proposed Observational Program	17	
Proposed Quantities Symbols	43	
Proposed Unit Names and Unit Symbols	43	
Q		
Quantum Limit	10	
Quantum Measurement	7, 12, 21	
Quantum Paradoxes	12	
Quasi-Phase Matching	24–25, 27, 29–30	
R		
Randomized Complete Block Design	32–33	
also: RCBD		
Relation to Process Philosophy and Category Theory	9	
Relativistic and Temporal Paradoxes	13	
Removal Efficiency	1, 3–4	
Resolving Paradoxes and Coordinating Disparate Phenomena	12, 16	
S		
Sample Collection and Preparation	3	
SI Historical	41	
Statistical Analysis	33	

Stimulated Raman Scattering .. 24–25, 28, 30
also: SRS
Structure Formation 7–8, 11, 17
Surface Area 1–2, 4

T

Temperature 3, 24, 33, 41, 44–46

Topological Quantum Computing 7, 19
Total Dry Matter 32–33, 35, 39
also: TDM

U

University of Agricultural Sciences .. 32–33, 40
also: UAS

Y

Yield Attributes 32–33, 36, 39

Z

Zea Mays 32
Zeno's Paradoxes 14, 23

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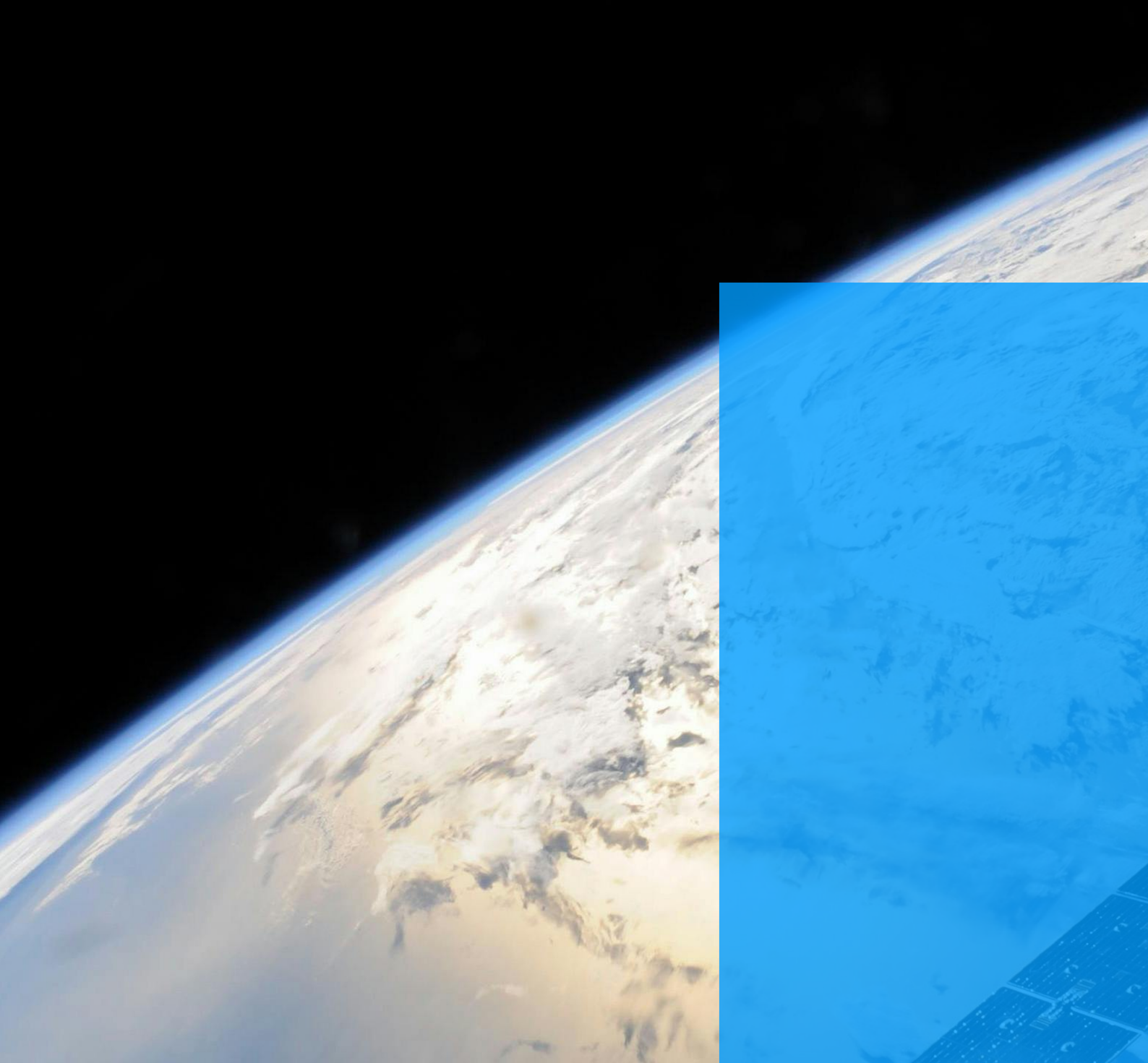
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