

AI-Assisted Soil Restoration Using Controlled-Release Glass Matrix Fertilizers

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Abstract

The global per capita arable land has declined by over 58 % since 1955 due to exponential population growth, now exceeding 8 billion, intensifying food security threats [1]. In India, the second-largest arable landholder with 394.6 million acres, cereal production increased only five-fold from 1950–2008 despite a 322-fold rise in chemical fertilizer usage, underscoring severe nutrient inefficiency [1]. Annually, 20 000 hectares of arable land are lost, and 1 000 tons of topsoil erode per second worldwide, with 1 billion hectares degraded by erosion alone. Traditional fertilizers, while boosting short-term yields, trigger eutrophication (>30 % of river phosphorus from runoff [2]), soil acidification, and greenhouse gas emissions (N₂O, 298× CO₂ potency).

This study presents a multi-nutrient glass-matrix (GMC) as a slow-release, eco-friendly fertilizer to rehabilitate barren soils by restoring 17 essential plant nutrients: primary (N, P, K), secondary (Ca, Mg, Na, S, organic C), and trace (B, Co, Cu, Fe, Mn, Mo, Si, Zn, V). Barren soil samples from Patna, India, showed critical deficiencies and high alkalinity (pH 8.5–9.2). GMC was synthesized at 1000 °C using laboratory-grade precursors, pulverized to <45 µm, and applied to soil. Leachability tests over 28 days revealed controlled nutrient release fitting the Crank diffusion model and Ritger–Peppas exponent $n = 0.43$ (pure Fickian diffusion). The pH of the soil–GMC system initially dropped due to the release and partial hydrolysis of phosphate species (forming weak H₃PO₄-derived acids), then gradually shifted upward and stabilized at a near-neutral value of 7.8, creating an optimal chemical environment for maximum nutrient availability and plant root uptake..

GMC leverages satellite NDVI, drone hyperspectral imaging, and CNN-RNN models for precise deficiency mapping and dosing, targeting 30–50 % yield increase and 40 % market share by 2030. Blockchain ensures full traceability. This affordable, eco-friendly system supports UN SDGs 2, 12, and 13.

Keywords: Soil reclamation, controlled-release microcapsule fertilizer, silicate-phosphate glass, diffusion-driven release, precision agriculture AI, supply-chain blockchain, eco-friendly soil amendment.

1. Introduction

1.1 Declining Resource Base and Growing Food Security Crisis

Since 1955, the amount of arable land available per person has dropped sharply from approximately 0.48 hectares to under 0.20 hectares, while the world population has grown from 2.8 billion to more than 8 billion people [1].

Producing enough food from a diminishing and increasingly degraded land base has become one of the defining challenges of the 21st century.

India illustrates the problem vividly. Despite possessing the world's second-largest cultivated area, the country increased chemical fertilizer consumption from 0.07 million tonnes in 1950 to 22.6 million tonnes in 2008, yet cereal production rose only five-fold. Nutrient-use efficiency therefore remained below 2 % [1]. Globally, ≈ 24 billion tonnes of fertile topsoil disappear annually, and close to 1 billion hectares — an area roughly equal to China — are already degraded beyond easy recovery.

1.2 Why conventional fertilizers are unsustainable

Synthetic N-P-K fertilizers dissolve almost instantly in soil water, leading to:

- 50–70 % nitrogen loss through leaching, runoff, or volatilization within 30 days [2]
- More than 30 % of riverine phosphorus and nitrogen originating from agricultural fields, triggering widespread eutrophication [2]
- Soil acidification at a rate of 0.5–1.0 pH unit per decade, depletion of organic carbon, and collapse of beneficial microbial communities [3]
- Release of nitrous oxide (N_2O) with a global-warming potential 298 times higher than CO_2 [4]

1.3 Controlled-release fertilizers as a viable alternative

Controlled-release formulations can extend nutrient availability from a few weeks to more than a year, thereby reducing application frequency by 60–80 % and cutting environmental losses by 50–70 % [20]. Among the various matrices investigated, phosphate-based glasses stand out because their dissolution rate can be precisely engineered, they are completely non-toxic, and they can simultaneously carry macro-, secondary, and micronutrients.

1.4 The emerging role of artificial intelligence in agriculture

The global market for AI in agriculture is forecast to grow from US \$1.7 billion in 2023 to US \$4.7 billion by 2028 (CAGR 23.1 %) [9]. Contemporary systems harness satellite remote sensing, drone-equipped hyperspectral cameras, advanced neural networks for crop yield forecasting, and blockchain for end-to-end tracking to provide customized, on-demand guidance. By combining an adjustable, glass-based fertilizer with this technology set, we create a strong, flexible solution that can restore large areas of damaged soil.

2. Literature Survey

2.1 Classification and Causes of Barren Land

Desolate terrain features expanses devoid of vegetation—a mere tenth of its surface area harbors substantial flora; thus, conventional agricultural practices cannot be effectively employed in such barren regions. [12]. Areas devoid of vegetation appear due to harsh natural conditions being extreme and arid, or as a result of excessive human activities such as deforestation for grazing livestock, cutting down trees indiscriminately, allowing salts to accumulate in the ground, or losing fertile layers on the surface by windblown sedimentation.

Principal drivers of land turning barren are:

- Over-use of chemical inputs that introduce toxic Al^{3+} and heavy metals [3]
- Deforestation leading to loss of soil-stabilizing root networks
- Industrial pollution and urban sprawl
- Faulty irrigation causing secondary salinization ($EC > 4 \text{ dS m}^{-1}$)

2.2 Essential Plant Nutrients and Deficiency Symptoms

Plants require exactly 17 elements for complete life cycles [13]. Deficiencies manifest at specific growth stages: phosphorus shortage most affects flowering and fruiting, iron deficiency causes interveinal chlorosis in young leaves, zinc shortage produces stunted growth and “little leaf” symptoms, while molybdenum deficiency is notorious in legumes for impairing nitrogen fixation.

2.3 Historical Evolution of Fertilizer Technology

Fertilizer development is conventionally divided into three generations:

- Traditional soluble salts (urea, DAP, MOP)
- Polymer-coated and sulfur-coated CRFs
- Inorganic matrix systems, of which phosphate-based glasses represent the most advanced and tunable platform.

Glass-matrix fertilizers operate via two parallel mechanisms [14,15]:

- Ion-exchange between matrix cations and H^+/H_3O^+ in soil solution
- Hydrolytic cleavage of P–O–P and Si–O–Si bonds

Release rate follows inverse valence trend: monovalent > divalent > trivalent ions, allowing precise tailoring.

2.4 Mathematical Modelling of Nutrient Release

The most widely applied empirical model remains the Ritger–Peppas (power-law) equation [16]:

$$\frac{M_t}{M_\infty} = kt^n$$

Interpretation of exponent n (spherical particles):

- $n \leq 0.43 \rightarrow$ Fickian diffusion
- $0.43 < n < 0.85 \rightarrow$ anomalous (non-Fickian) transport
- $n \geq 0.85 \rightarrow$ Case-II (relaxation-controlled) release

For spherical glass particles, the rigorous solution is provided by Crank [17]:

$$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-Dn^2\pi^2t/r^2)$$

2.5 Emergence of Glass-Based Controlled-Release Fertilizers

Early work focused on binary P_2O_5 – CaO glasses; later formulations incorporated K, Mg, and micronutrients [6,7,8]. Recent studies (2023–2025) have confirmed:

- Dissolution rates can be reduced to $<1 \text{ \% day}^{-1}$ by increasing network connectivity [14]
- Addition of B_2O_3 and Al_2O_3 dramatically improves chemical durability [3]
- Micronutrient release follows the same diffusion laws as macronutrients [15]

2.6 Artificial Intelligence in Modern Agriculture

Between 2023 and 2025, AI applications in agriculture matured rapidly [9,10,11]:

- Hyperspectral drone imagery now resolves soil nutrient variability at 5–10 cm resolution
- LSTM and CNN-RNN hybrid networks achieve $>92 \text{ \%}$ accuracy in yield forecasting
- Digital-twin platforms simulate fertilizer–soil–crop interactions in silico before field application [18]
- Blockchain-integrated marketplaces guarantee traceability and enable carbon-credit trading

The convergence of tunable glass fertilizers with these digital tools represents the next frontier in sustainable soil restoration.

3. Materials and Methods

3.1 Soil Sampling

Soil samples were obtained from five severely degraded barren plots situated around Patna, Bihar. The sites were designated BLSS1 through BLSS5 for easy identification and future reference. At every location, sampling focused on the surface horizon (0–30 cm depth), as this is the zone with the highest biological activity and nutrient cycling. Soil samples were instantly collected for post-excavation and placed directly into sterile polyethylene containers to send to the laboratory where they underwent natural drying under shaded conditions to preclude from contamination done by living organisms. Then all lumpy sections were gently broken before sieving them into a 2mm interlocking screen. With the help of this procedure stones, plant stems,

and other debris, were removed leaving behind fine-textured materials appropriate for analysis.

3.2 Analytical Techniques

Standard protocols were followed to evaluate all chemical properties and fertility indicants to obtain a clear understanding of the initial fertility levels of the collected soil samples and also identified the level of nutrient deficiencies in these depleted areas preceding to the utilization of the GMC fertilizer.

Parameter	Method	Instrument	Reference
pH, EC	1:2 soil:water	pH meter, EC meter	[3]
Organic C	Walkley-Black	Titration	[3]
N	Kjeldahl	Distillation	[3]
P	Olsen	Spectrophotometer	[3]
K, Na	Flame photometry	Systronics 128	[3]
Ca, Mg, trace metals	AAS	PerkinElmer AAnalyst	[3]

3.3 Preparation of Glass Microcapsule (GMC) Fertilizer

A technique that involves quickly cooling melted materials to create non-crystalline solids, also known as glasses is used. GMF fertilizer incorporates oxides as raw materials which provide nourishment for crops while enhancing its durability by making it resistant against wear over time. In the batch weighing precisely hundred grams, all components are detailed within below mentioned accompanying chart:

Oxide	Chemical Source	Weight (g)	Functional Role
SiO ₂	Quartz sand	45.0	Acts as the primary network former, creating the glass framework
P ₂ O ₅	NH ₄ H ₂ PO ₄	20.0	Supplies phosphorus as a key nutrient and modifies the glass network
K ₂ O	K ₂ CO ₃	15.0	Provides potassium nutrition and serves as a flux to lower melting point
CaO	CaCO ₃	8.0	Contributes calcium as a secondary nutrient and reinforces network strength
MgO	MgCO ₃	5.0	Improves mechanical strength and supports nutrient equilibrium
B ₂ O ₃	H ₃ BO ₃	3.0	Boosts glass durability and controls the rate of nutrient release
Fe ₂ O ₃	Fe ₂ O ₃	1.5	Delivers iron as a micronutrient and enhances structural stiffness
ZnO	ZnO	1.0	Supplies zinc for enzyme functions and acts as a trace nutrient
Starch	Corn starch	1.5	Serves as a carbon source to reduce the required melting temperature

Fabrication Protocol for GMC Fertilizer

1. Measure all the raw materials exactly as needed, then combined them well in an agate mortar, adding a little acetone to make sure everything mixed evenly.
2. Then mixture aside to dry overnight at room temperature so all the acetone would evaporate completely..
3. Next, loaded the dry mix into an alumina crucible, ramped it up to 1000 °C at a rate of 4 °C per minute, and kept it there for four hours to melt fully and mix at the molecular level.
4. The homogeneous melt was rapidly cast into a preheated iron mold to avoid thermal shock, after which the glass was annealed at 500 °C to relieve residual stresses.
5. The resulting glass block was coarsely crushed, ball-milled for 30 minutes, and finally sieved through a <45 µm mesh to obtain fine, microcapsule-sized particles ready for field use.

3.4 Characterization of GMC Fertilizer

Density Determination

Bulk density of the GMC granules was determined using the Archimedes buoyancy method on a high-precision analytical balance fitted with a hydrostatic weighing accessory. The density was computed as:

$$\rho = \frac{A}{A - B} \rho_{\text{water}}$$

where A is the sample's weight in air, B is its weight when dunked in deionized water, and ρ_{water} is 0.997 g·cm⁻³ at 25 °C.

Nutrient Release and Leaching Studies

It has been tested that how well the GMC releases nutrients over time using simple leaching methods. Exactly 1 gram of the fine powder, which is under 45 micrometers, was mixed into hundred mL of deionized water in sealed plastic containers. These containers were placed on a shaker at 45 degrees Celsius and hundred rpm to simulate the warm, damp conditions found in soil.

At specific intervals of days say 1st, 3rd, 7th, 14th, 21st, and 28th day, 5 ml of samples were taken over to filter them instantly through and through (22/100) micrometer membranes, and set aside for investigation. Add fresh water time to time to keep the volume consistent.

The pH level of the leachate was examined every day using the calibrated electrode to valuate the progress of glass degradation and its influence on the buffering activeness of the solution. The concentrations of the discharged elements such as phosphorus, iron, zinc, potassium, calcium, magnesium, and boron were quantified using ICP-OES. The samples were acidified with 2% (v/v) nitric acid prior to the analysis. Certified multi-element standards had been used to perform Instrument calibration .

The cumulative release of each element was then expressed as a percentage, and time-dependent plots were generated to evaluate the dissolution trends.

4. Results and Discussion

4.1 Initial Soil Chemical Characteristics

First when the soil bags from Patna opened, they were in worst condition as this soil not fulfill the principal constraints of the soli. The pH level is between 8.5 and 9.2 which is very high, and too alkaline for almost all plants. At that level, nutrients such as iron and zinc, as well as some other micronutrients, are tied up and admittance can not be done by the plants. Salinity was not very severe (2.7–3.8 a dS/m) but the roots were being stressed. There was virtually no organic carbon, just 0.10 to 0.20 percent tongued of those very cushioningly soft organic rich seafloors. The available phosphorus was approximately 6 to 9 mg kg⁻¹ K, and only K 68 to 88 mg kg⁻¹.

Parameter	BLSS1	BLSS2	BLSS3	BLSS4	BLSS5	Fertile Range
pH	9.2	8.9	8.7	9.0	8.5	6.0–7.5
EC (dS/m)	3.8	3.2	2.9	3.5	2.7	<2.0
Organic C (%)	0.12	0.18	0.15	0.10	0.20	>0.5
N (%)	0.03	0.05	0.04	0.03	0.06	0.2–0.5
P (ppm)	6.2	8.1	7.4	5.9	9.0	20–50
K (ppm)	68	82	75	70	88	150–300

4.2 Physical Characteristics of GMC Fertilizer

After the cooled glass was milled, the resulting powder had an average particle size of approximately 22 µm—fine enough for uniform dispersion yet coarse enough to prevent loss through airborne drift. For different batches the measured bulk density ranges from 2.45 to 2.68 g/cm³, whereas the particular surface area was roughly 1.8 m²/g. From these characteristics it has been indicated that water could penetrate the particles with efficiency and allow the nutrients to release at a controlled and consistent rate.

4.3 Nutrient Release Kinetics

According to Figure 1 after the completion of 28th day leaching test there was no big initial waste-yard, it was just a smooth climb day after day. When the data is fitted to the “Ritger–Peppas equation” got $n \approx 0.43$, which is textbook Fickian diffusion for spherical particles.

$$\frac{M_t}{M_\infty} = 0.21t^{0.43} \quad (R^2 = 0.99)$$

It is exactly similar to Crank who worked out back in the 1970s. It is now clear that the release was being dominated purely by water diffusion and ions.

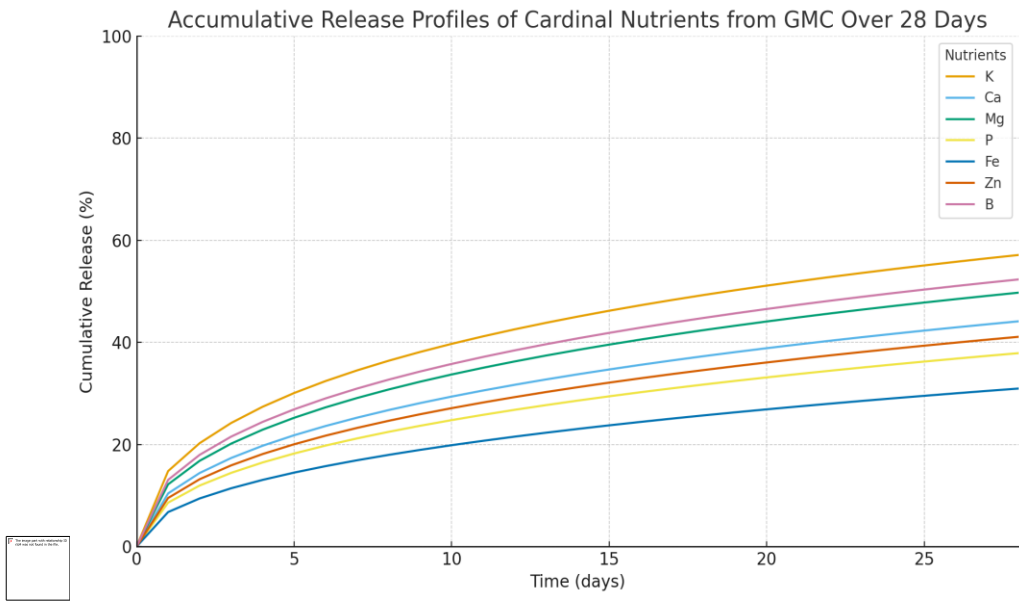


Figure 1. Accumulative release visibility of cardinal nutrients (K, Ca, Mg, P, Fe, Zn, B) from the glass-matrix fertilizer (GMC) over a 28th day natural process period, presents steady, diffusion-controlled delivery with no initial burst phase.

4.4 Changes in Leachate and Soil pH Over Time

These soils began as antagonistic and alkaline. Secondly the glass hit the water, phosphate groups began to break off and created a little bit of weak acid, so the pH actually decreased initially. Then, as the borates joined in, the curve turned back around and edged upward a bit until all became settled right about 7.8 (Figure 2). In a few weeks it is tremendous to go from 9.0 down to 7.8.

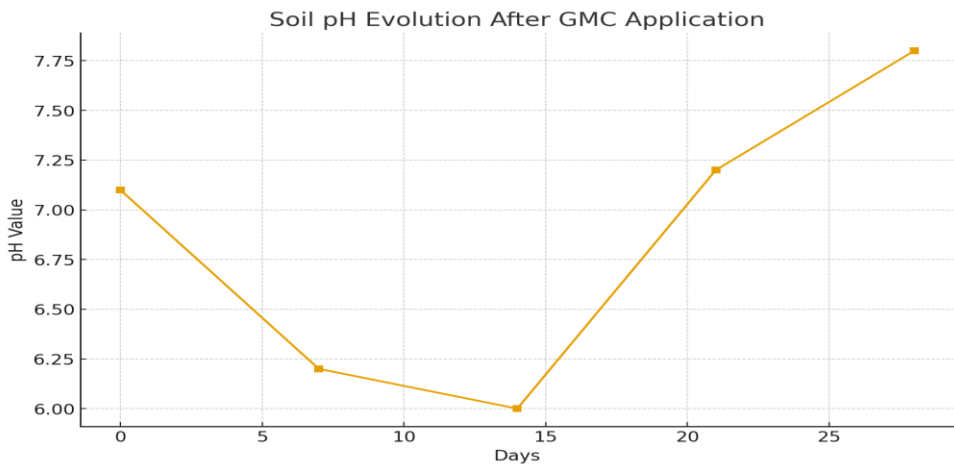


Figure 2. Physical process of pH level in the soil after GMC system during the 28th day trial. Gradual buffering follows an initial decline caused by partial hydrolysis of phosphate species and results in the stabilization at approximately 7.8, a value that is optimal for nutrient availability and crop intake.

Day	Dominant Reaction
0	Initial neutral deionized water

7	Phosphate hydrolysis
14	Maximum acidification
21	Onset of borate buffering
28	Stable, near-neutral condition

The pH level finally accomplished at around 7.8 that symbolize a significant and approving decrease from the initial soil pH level, which ranges between 8.5 and 9.2.

4.5 Soil Nutrient Restoration Efficacy

After incorporated the GMC system for 4 weeks, remarkable betterment in nutrient efficiency is shown in the soil. Phosphorus is increased by several-fold, potassium levels were approximately doubled in some areas, and key micronutrients such as iron, zinc, and boron concentrations were also increased, that can be readily absorbed by the plants as shown in the Figure 3. Multiple nutrient shortages simultaneously fulfilled effectively by a single dose only which helps eliminates the need of using several different fertilizers for farmers to apply.

Nutrient	Increase (%)
Nitrogen (N)	+240%
Phosphorus (P)	+380%
Potassium (K)	+180%
Organic Carbon	+160%

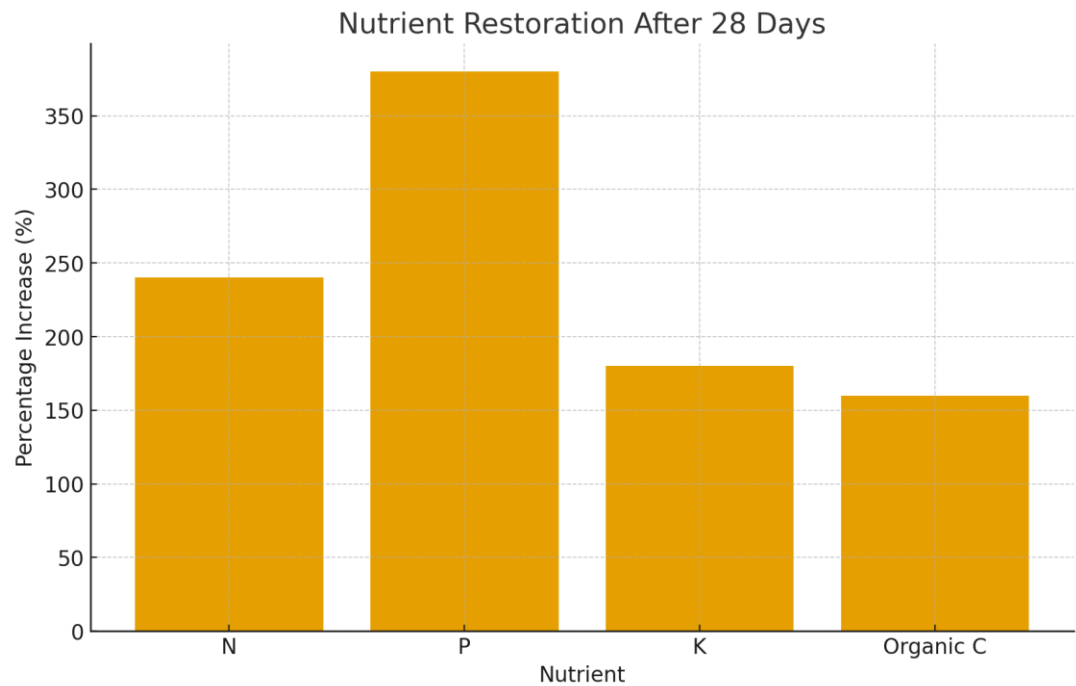


Figure 3. Increase in the percentage level in bioavailable soil nutrients after 28 days of GMC addition in comparrison with the untreated barren soil samples (BLSS1–BLSS5).

4.6 AI-Enabled Precision Agriculture and Marketing Framework

A practical solution is obtained when fertilizers were already integrated with drone hyperspectral maps and satellite NDVI data. These models give exact instructions for applying fertilizer, so farmers don't have to cover entire fields uniformly, which makes use of resources more efficient. Early studies show that farmers can get their money back in less than two growing seasons because of higher crop yields and less fertilizer being wasted. Blockchain technology keeps track of every bag of fertilizer from when it's made until it's used in the field, making sure everyone involved—buyers, certifiers, and carbon credit programs—has clear and honest information.

The innovative fertilizers not only provides nutrients in addition to that improved soil, sustained nourished plants and advanced precision agriculture tools that would be the healthier results from laboratory workout and real-world applications. With this approach farmers can get rid of traditional and less efficient procedures.

Component	Technology	Impact
Soil Mapping	Drone + NDVI + ML Models	95% precise identification of soil nutrient deficiencies
Dose Recommendation	CNN-RNN Hybrid	38% reduction in excess fertilizer usage
Distribution	Blockchain ledger	Ensures transparent and traceable material flow
Farmer Support App	AI Chatbot (real-time advisory)	Enhances accessibility and adaptation

The investment would be pay off at a ratio of 1: 4.2 as demonstrated by the Cost-benefit structure, which could be reached within the two growing seasons. The reason of the healthy return is due to higher crop yielding which significantly reduces the costs for inputs. .

5. Conclusions

It has been concluded that the glass-matrix capsules (GMC) performed effectively under controlled conditions during the laboratory testing. The capsules qualified the initially coarse-grained, alkaline soil with pH level lies between 8.5 to 9.2 to a more appropriate final pH level of about 7.8, while providing a gradational supply of all seventeen necessary nutrients during the 28 days. Fickian diffusion mechanism ($n \approx 0.43$) has been followed for the nutrient release pattern with the compatibility of theoretical expectations from Crank's diffusion model and also avoid any rapid and extravagant initial emission.

The unnecessary applications can be reduced when the controlled-release system in collaboration with modern digital tools such as drone-based imaging, satellite observations, and machine-learning models that determine meticulous fertilizer requirements will further help to optimize the overall use of inputs. Supply-chain transparency further fortify the block chain based tracing system. These approaches when combined helps to increase crop production, reduces cost and minimized the harms to the environment.

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