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Application the of G.R.O.W.S (Green Revival of Worn-out Soil) Microcapsules: Tailoring Nutrient and Microorganism Content for Soil Fertility Enhancement

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Abstract: Climate change has catalysed an increase in global food demand and led to food insecurity. Population growth and adverse impacts on agricultural lands has strengthened pressure on the production of food. The root of this issue is soil degradation. Soil degradation arises from agricultural, industrial and commercial pollution, the reduction of cultivation land due to urbanisation, overgrazing and unsustainable agricultural practices as well as global warming. To mitigate soil degradation and increase food production, numerous strategies have been implemented such as the use of animal manure, chemical fertilisers and organic fertilisers. However, these practices have been proven to be relatively inefficient and ineffective on a large scale. They are also unsustainable for the environment. Recent studies and papers showcase that one of the most efficacious methods for rejuvenating infertile soil and converting it into fertile soil is the implementation of precise microbial and nutrient interventions. The systematic release of essential nutrients and microorganisms will not only transform the soil into a fertile state, fostering a stable ecosystem for crop production, but also serves to prevent issues such as nutrient leaching, runoff, volatilization, denitrification. This approach holds great promise for significantly increasing crop production to meet the burgeoning crop global demands.

Keywords: *Infertile Soil, Fertile Soil, Controlled-Release, Nutrient Leaching, Microbial Activity, Macronutrient.*

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I. INTRODUCTION

Global food demand is projected to increase by approximately 30% to 62% by 2050 with the population at risk of hunger to increase from −91% to +30 between 2010 and 2050 (van Dijk et al. 2021) The food shortage is exasperated by an increasing loss in fertile soil caused by a variety of issues such as natural disasters, wildfires, slash and burn technique of cultivation and land abandonments.

Some aggravators of global food insecurity are volatile food prices, population growth, increasing pressure on food production due to climate change, and decrease in natural resource availability for plant growth. The root of these challenges is the rapidly accelerating crisis of land and soil degradation.

Over the past few decades, soil fertility has extensively decreased due to intensive farming practices like deforestation, overgrazing, intensive cultivation, slash and burn practices, forest fires and construction work. The demand for food, fibre and other natural resources derived from the soil has exponentially increased the pressure on soil ecosystem, rendering it vulnerable to erosion by wind and water. This, in turn, exacerbates soil degradation.

At the current rate of 24 billion tons of fertile land lost annually (Abdel Rahman, 2023), this crisis will pose an extremely life-threatening issue of food shortage by 2050.

This alarming trajectory underscores the urgent need for more fertile agricultural land. The measures implemented to address the impending food shortages such as use of animal manure, chemical fertilizers and other traditional soil management techniques have been inadequate in the goal to mitigate the crisis. This is proved by the Food Security Information Network's analysis, which underscores the persistence and scale of the problem. (Food Security Information Network & Global Network Against Food Crises, 2025) The most direct and effective way to reduce soil

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degradation is a complex method of conversion of infertile soil to fertile soil.

Chemical fertilisers give rise to several problems such as nutrient leaching. (Kulkarni & Goswami, 2019) They lead to deterioration of soil health, contamination of groundwater and negative impacts on human and animal life. Thus, recent years have seen a rise in organic fertilisers which protect soil health. However, due to their dependence on microbial activity, which is almost non-existent in infertile soil, organic fertilisers act slowly and ineffective. Hence, although current technologies provide us a base to develop solutions, are unable to provide a scalable and sustainable solution and require innovative thinking and research analysis to find an effective solution.

To build on these solutions and answer these problems, the following research paper introduces a solution of microcapsules that contain tailored amounts of microorganisms and nutrients to increase fertility in infertile soil or partially infertile soil (specifically Infertile Soil caused by the death of microbes or lack of nutrients, excluding infertile soil created through desertification.)

II. MATERIAL AND METHODOLOGY

Fertile soil is an interconnected network and ecosystem made up of a complex mixture of minerals, micro-organisms and other chemicals that enable plant growth and/or plant safety.

The Microcapsule aims to increase the fertility of infertile soil by catering precisely to the needs of the soil and the growth of the plants by setting the amounts of macronutrients and micro-organisms along with other compounds to help face other issues.

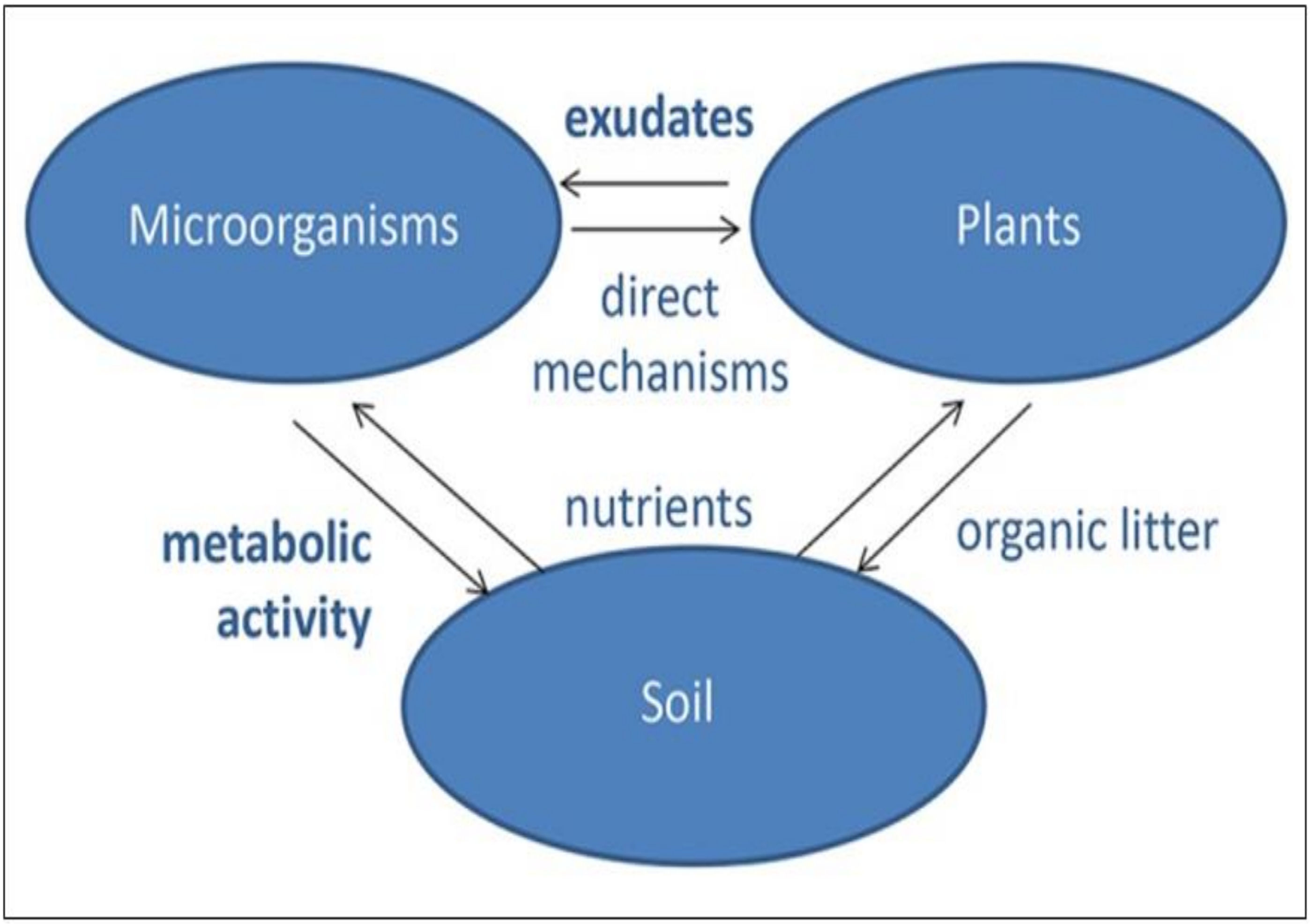

Fig 1 Mind map Showcasing the Relation between Soil and its Components. (Jacoby et al., 2017)

A. The Tailoring Algorithm:

The tailoring algorithm is a salient feature of the microcapsule system which takes in soil data of the region it has to be deployed in and compares the current nutrient and soil microbe conditions among many other soil health checks (including but not limited to soil pH, temperature, hydrophobicity) to the average and the healthiest amounts of each of these conditions in fertile soil. It cross-checks the kind of vegetation that could grow in these weather conditions and compares the requirements of the different kinds of vegetation. Equipped with this data, it uses Artificial Intelligence to create a composition map of each of the microcapsules depending on what is required by the soil. The Tailoring Algorithm has a slightly different function once crops are growing in soil, it calculates the nutrient demand of the crops, and releases only that much to prevent nutrient leaching.

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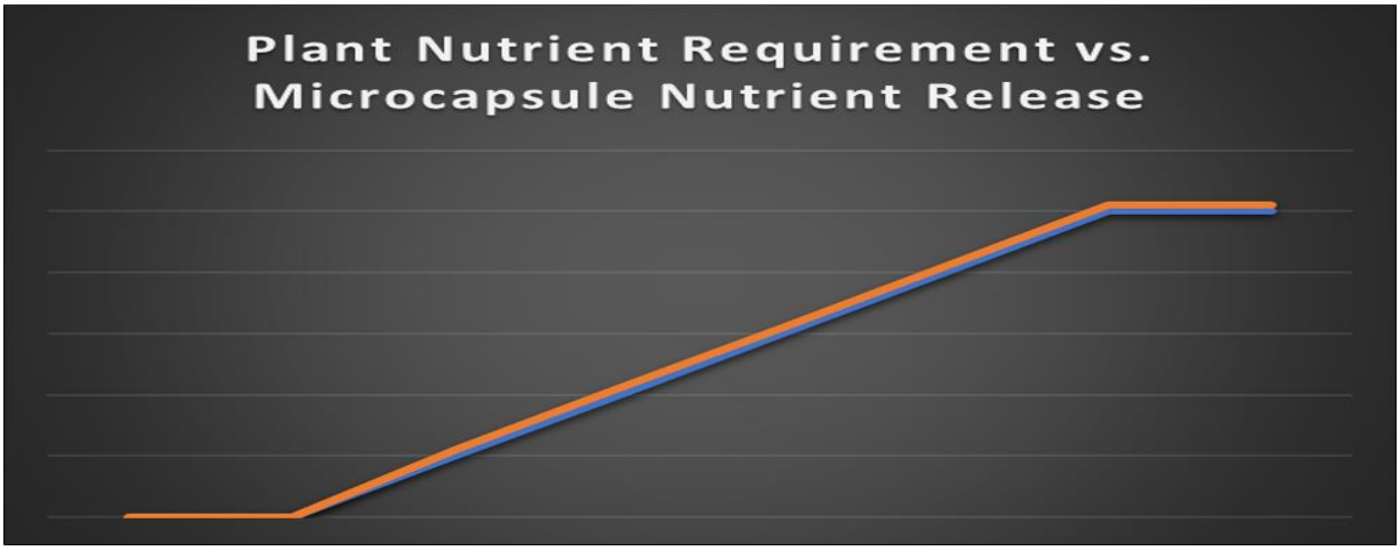

Fig 2 Line Chart of Plant Nutrient Requirement (Orange) vs Microcapsule Nutrient Release (Blue)

B. Contents of Fertile Soil and their Importance

➢ *Nutrients*

Soil must contain 7 basic macro-nutrients with Nitrogen, Phosphorus, Potassium, Sulphur and Magnesium being the most necessary. The secondary tier includes other elements required in smaller amounts such as Copper, Nickel, Molybdenum.

Addition of other micro-nutrients such as silicon (Si), iodine (I), selenium (Se), chromium (Cr), vanadium (V), arsenic (As), sodium (Na), and cobalt (Co) benefits some plants. These nutrients aid the plant in its metabolic processes. Maintaining perfect balance of these elements is crucial for plant growth. Additionally, increasing the rate of fertility. This has been explained and proved by Justus von Liebig's Law of the Minimum. The Law of the Minimum states that plant growth will be limited by the essential element that it is most deficient in. This graph gives an insight into the Law of the Minimum.

Each microcapsule would include all the above-mentioned macronutrients with varying amounts depending upon the needs of the soil and its environment according to tailoring algorithm.

However, most nutrients cannot be absorbed in their pure form so some of the nutrients are stored in the form of different compounds. Potassium is stored in the form of its compounds of Potassium Chloride or Potassium Sulphate; Phosphorus is stored in the form of grinded particles of Rock Phosphate (as a naturally occurring mineral, Rock Phosphate also contains calcium, Sodium and Magnesium as impurities. However, it could also contain Carbonate as an impurity and therefore Orthophosphates may be more viable.) Calcium could be added in the form of Gypsum. Magnesium in the form of micro-crystallised magnesium ore powder.

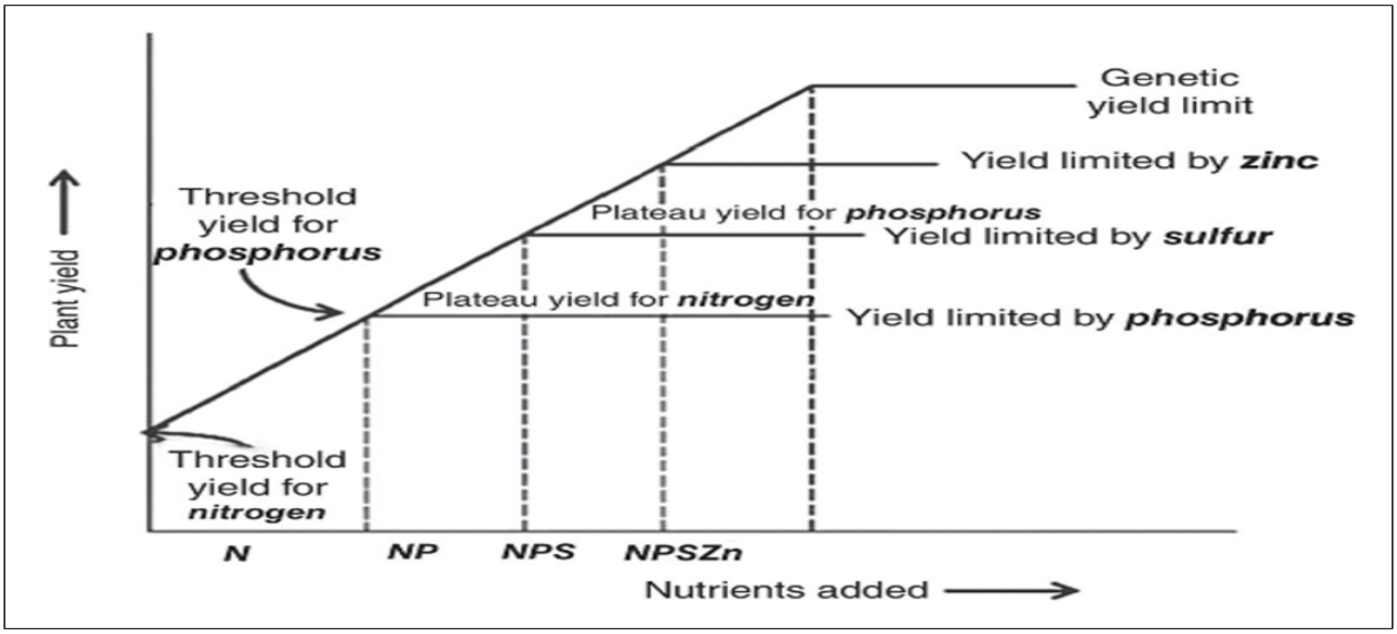

Fig 3 The Law of Minimum- (Sanchez, 2019)

➢ *Micro-Organisms*

In their natural environment, plants are part of a rich ecosystem including numerous and diverse microorganisms in the soil. It has been long recognized that some of these microbes, such as mycorrhizal fungi or nitrogen fixing symbiotic bacteria, play important roles in plant performance by improving mineral absorption and fixation.

Micro-organisms have a few key functions, a major portion of microorganisms such as nitrogen fixing symbiotic bacteria or phosphorus stabilizing bacteria liberate important nutrients from their respective compounds, others are responsible for destroying pathogens and harmful micro-organism, finally many micro-organisms form symbiotic relationships with plants and/or plant roots. The most perfect yet common example is that of Mycorrhizal Fungi, when in a symbiotic relation with a plant, increase root surface area, improve nutrient and water absorption, and support hormonal and nutritional balance in plants growing in a variety of soil types. These connections also help the plant absorb nutrients and water from a lot of soil more effectively, which lessens stress on the plant and promotes optimal development rates. Mycorrhizal fungus also aids plants in adapting to new soil conditions by giving them nutrients and water to lessen transplant shock, which eventually increases plant growth and stress tolerance. Each capsule will receive all major different strains of microorganisms as mentioned in Table 2 along with Mycorrhizal Fungi.

➢ *Other Compounds*

Infertile Soil is impacted by various other factors as per the region. Each microcapsule will therefore be equipped with special compounds in its contents. Such as, soil pH can be increased by Lime. Soil pH can be decreased by addition of Elemental Sulphur. Soil Hydrophobicity can be reduced by the addition of all Calcium Compounds, which are already added in the form of Gypsum. Soil Structure can improve by the addition of compounds already included in the microcapsules such as phosphorus compounds, Gypsum and Lime. Salinity can be reduced by the already present Elemental Sulphur and Gypsum. Sodicity can be reduced by the introduction of Calcium Chloride which displaces sodium ions and reduces sodicity without nutrient leaching. These are some basic requirements to create a conducive soil ecosystem which is provide by the microcapsules. However, this will differ from region to region depending on climate and reason for infertility.

III. CONTROLLED RELEASE MECHANISM OF THE MICROCAPSULES

A. Materials Used for the Microcapsule

With the goal of making this method sustainable, it is important to use sustainable and biodegradable material for the capsule itself (i.e. the outermost covering of the microcapsules). For such a function bioplastics are suggested. These are a fast-developing family of polymeric substances that are frequently promoted as substitutes to petroleum-derived plastics. The bioplastic used would be Polyhydroxyalkanoates (PHAs). Specifically, a copolymer of PHA could be used such as PHBV (poly(3-hydroxybutyrate-co-3-hydroxyvalerate))

According to Sudesh, Abe, and Doi (2000) PHBV's elastic and impact-resistant property allows it to withstand physical stress. PHBV degrades naturally in soil by microbial activity into CO_2, water, and biomass. Further, the rate of degradation can be adjusted according to the soil ecosystem by varying the 3-hydroxyvalerate (HV) content. The microstructure of PHBV also allows gradual water infiltration, enabling a slow and sustained release of the capsule's contents. This allows for controlled release of the nutrients and microorganisms. Hence, it integrates into the natural carbon cycle without causing long-term environmental harm, leaving behind no microplastics.

B. Method of Release

➢ *Hydration:*

Upon contact with soil moisture, the microcapsules begin to hydrate and swell, initiating the controlled-release mechanism.

➢ *Geothermal Energy:*

The temperatures under the soil will melt the outer covering of the microcapsule to release the nutrients

➢ *Nutrient and pH Modifier Release:*

As the outer covering of microcapsule melts or dissolves, the nutrients are released in a slow and controlled release ensuring that essential nutrients are available to plant roots, reducing nutrient leaching and runoff.

➢ *Beneficial Bacteria Activation:*

Simultaneously, the hydrated microcapsules activate the beneficial bacteria strains. These bacteria colonize the soil and contribute to improved nutrient cycling, disease suppression, and overall soil health. Their release is also gradual, allowing for sustained microbial activity.

IV. RESULTS AND DISCUSSION

The G.R.O.W.S microcapsule has potential to convert infertile soil to fertile soil, reason being that Primary Data proves that both its tailored content, slow-release method and its contents have some potential in the conversion of infertile soil to fertile soil.

A. Primary Data:

A study conducted in the Onattukura sandy plains of Kerela, India (G Raj, 2019) involved fertilisation of the plains with an organic matrix based slow-release fertilizer. It was found to be effective under Onattukara condition for increasing the nutrient use efficiency from 18% to 44%. The results showed 50% reduction in the recommended dose of fertilizer, reduced the cost of cultivation and loss of nutrients and increased the nutrient use efficiency and yield in the Onattukara sandy plain. This increase in crop yield through scheduled release of nutrients and microorganisms has been shown in a variety of different regions through various research and experimentation. This data brings to light the

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credibility of the theoretical G.R.O.W.S capsule which works on a similar slow-release principle to aid in the fertility of soil even less fertile than the Onattukara sandy plains of Kerela.

Another study (Sharma & Singh, 2011) reported that an Organic Matrix based slow-release fertiliser which was used in parallel to a chemical fertiliser of boron, Sulphur, and nitrogen, both of which had 2 different variants which had different amounts of their contents. The Organic Matrix based Slow-Release Fertiliser with the higher concentration (736.5 kg/ha in comparison to the lower concentration of 542 kg/ha) released ammonium up to 50-d in wet soil under laboratory conditions which showed maximum retention of the nutrients. It showed significant increase in plant growth, nitrate assimilation and seed yield. It noticed the greatest percentage increase in biomass production at 65.8% in root fresh weight, 38% in root dry weight, 45.9% in leaf fresh weight, and 27.5% in lead dry weight plant. It also boosted nitrate uptake and assimilation from the plant's rhizosphere, as evidenced by a 45.6% increase in nitrates, 27.5% in nitrite, and 11.7% in nitrate reductase activity (NRA) in leaves of 45-day-old plants compared to control. The organic matrix-based SRF-II boosted seed yield by 28% in Indian mustard. Controlled Release mechanism shows potential and even increased potential in infertile soil due to infertile soil's requirements for targeted supply of nutrients to rebuild the soil health by introduction of plants.

Further, the contents of the G.R.O.W.S Capsule are critical to the process. Infertile soil has low microbial activity and depleted nutrient supplies. Alternatively, the underlying causes of this infertility could be the abnormal soil pH, temperature, or texture. To rebuild an eco-system, the contents of the G.R.O.W.S capsule contains:

Mycorrhizal fungi, which are an essential catalyst in the revival of infertile soil. According to the documents ("Journal of Korean Society of Forest Science (한국산림과학회지) | Korea Science," n.d.), it can be found that the growth rate of tree seedlings is increased when Pisolithus tinctorius mycorrhizae are artificially inoculated. Through mycorrhiza formation, host plants may survive infertile soil having low nutrients and water contents. Thus, mycorrhizal fungi help to rejuvenate the ecosystem of infertile soils.

It contains all major nutrients for crop growth that have special significance in infertile soil. To rebuild the Infertile Soil into healthy, fertile soil, growing plants is a requirement, and to commence microbial activity along with nutrifying the soil. However, conventional fertilisers are incapable of doing this, especially in infertile soil as they only have practical implications in an already growing crop patch. Therefore, the theoretical Microcapsule is uniquely fitted for such a role. Reason being that the G.R.O.W.S capsule contains all major macronutrients and bacteria that are required by plants. Adapting research from scientists (Barker, 2021), which recorded percentage of compositions of essential nutrients that are required for the efficient growth of healthy plants, the following conclusions have been made.

Table 1 Summarisation of Nutrient Concentration in Plants

Nutrient	**Ion or molecule taken up**	**Typical content in plant leaves**	**Element's main functions or a constituent of specific plant compounds**
Carbon	CO_2	50%	Cell growth, energy
Oxygen	CO_2, H_2O, some other ions below	40%	Oxidant
Hydrogen	H_2O	5%	Reductant
Nitrogen	NO_3^-, NH_4^+	3%	Protein, amino acids, DNA, RNA, chlorophyll
Potassium	K^+	2%	Electrolytic balance, protein synthesis, turgidity
Calcium	Ca^{2+}	1%	Pectin acts as "cement" between cells, mitosis, nodulation in legumes, bones in animals
Magnesium	Mg^{2+}	0.5%	Chlorophyll, photosynthesis, respiration, adenosine triphosphate (ATP; key to energy transfer during photosynthesis and respiration)
Sulphur	SO_4^{2-}	0.3%	The amino acids cysteine and methionine in protein synthesis, structural integrity of enzymes, characteristic flavours of garlic, onion and brassicas
Phosphorus	$H_2PO_4^-$, HPO_4^{2-}	0.2%	DNA, RNA, bones (in animals), energy (ATP), mitosis
Chlorine	Cl^-	100 ppm	Evolution of oxygen during photosynthesis
Iron	Fe^{2+}, Fe^{3+}	100 ppm	Chlorophyll synthesis, proteins, respiration, ATP synthesis, antioxidant, nitrogen-fixation. Increases in concentration of indole acetic acid, lignin's, flavonoids and aromatic amino acids
Manganese	MnO_4^{2-}	50 ppm	Required for photosynthesis and activation of some enzymes
Boron	BO_3^{3-}, H_3BO_3	30 ppm	Presumed to be needed for movement of sugar, lignification, pollination and seed development; no known enzymes contain boron, it is the least understood essential element

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Zinc	Zn^{2+}	20 ppm	Activator of several enzymes involved in nitrogen and carbohydrate metabolism, photosynthesis, DNA and RNA synthesis; main ones are alcohol dehydrogenase for respiration and carbonic anhydrase for photosynthesis
Copper	Cu^{2+}	5 ppm	Photosynthesis, respiration, reactions with molecular oxygen, antioxidant
Nickel	Ni^{2+}	1 ppm	Activity of urease, possibly nitrogen fixation
Molybdenum	MoO_4^{2-}	0.1 ppm	Nitrate reduction, nitrogen fixation

We can safely ignore the Carbon, Hydrogen and Oxygen Levels of the plant due to method of use and manner of absorption. This data brings to light the different macronutrients required by plants, and how their assimilation in infertile soil is a must to grow any plants in it.

Infertile Soil requires soil microbial activity, which must be commenced by its introduction to the soil. According to (Hayat et al., 2010), these are the major microorganism strains in fertile soil.

Table 2 A summarisation of important bacteria strains and its features

Micro-organism	**Function**
Azotobacter Strains: Azotobacter vinelandii Azotobacter chroococcum	Nitrogen Fixing Bacteria
Clostridia	Obligatory anaerobic heterotrophs capable of fixing N_2 only in complete absence of oxygen.
Azospirillum	Nitrogen-fixing organism living in close association with plants in the rhizosphere.
Acetobacter (Gluconacetobacter) diazotrophicus	Nitrogen Fixing Bacteria
Azoarcus sp. BH72	Nitrogen Fixing bacterium
Enterobacteriaceae genera (Klebsiella Enterobacter, Citrobacter, etc.),	Play various important functions. They have been identified as plant growth promoting bacteria (PGPB) due to their ability to promote root and shoot growth, nitrogen fixation, and solubilization of soil phosphorus.
Herbaspirillum	Various Functions. Are Plant Growth Promoting Rhizobacteria (PGPR).
Pseudomonas	Generally useful in plant growth and used in nutrient cycling. Some species associated and can contribute to plant growth promotion through phosphate solubilisation.
Bacillus	PGPR.
Rhizobium	Nitrogen Fixing Bacteria that form symbiotic relationships with leguminous plants.
Phosphatases	Solubilization of mineral phosphates and other nutrients, and improvement of soil structure and organic matter content are recognized functions

The theoretical G.R.O.W.S Capsule is perfectly designed to hold microorganisms in it and release them once in the soil, due to its ability to disperse these bacteria in soil, it has the ability to restart microbial activity in infertile soil, making it the perfect way to turn infertile soil fertile.

V. CONCLUSION

This method of controlled nutrient release of the nutrient and microorganisms aims to provide precise nutrient delivery to plant roots, minimizing wastage and environmental impact, and provides more efficient nutrient utilization by crops. The approach is particularly valuable for rehabilitating infertile or degraded lands, increasing efficiency, productivity as well as crop quality addressing nutrient deficiencies and pH imbalances. This method may also enhance the resilience of crops to climate change. It is a technique which reduces the risk of nitrogen leaching and runoff due to unorganized dispersion of nutrients. In summary, the theoretical G.R.O.W.S microcapsule is a multi-faceted approach, combining a tailored slow-release method and nutrient-rich contents, holds great promise in addressing the complexities of infertile soil, offering a sustainable solution for enhanced agricultural productivity and ecosystem restoration.

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