PROAGRO LECTORIUM

Sustainable Management of the Phosphogypsum Waste with Green and Innovative Approaches

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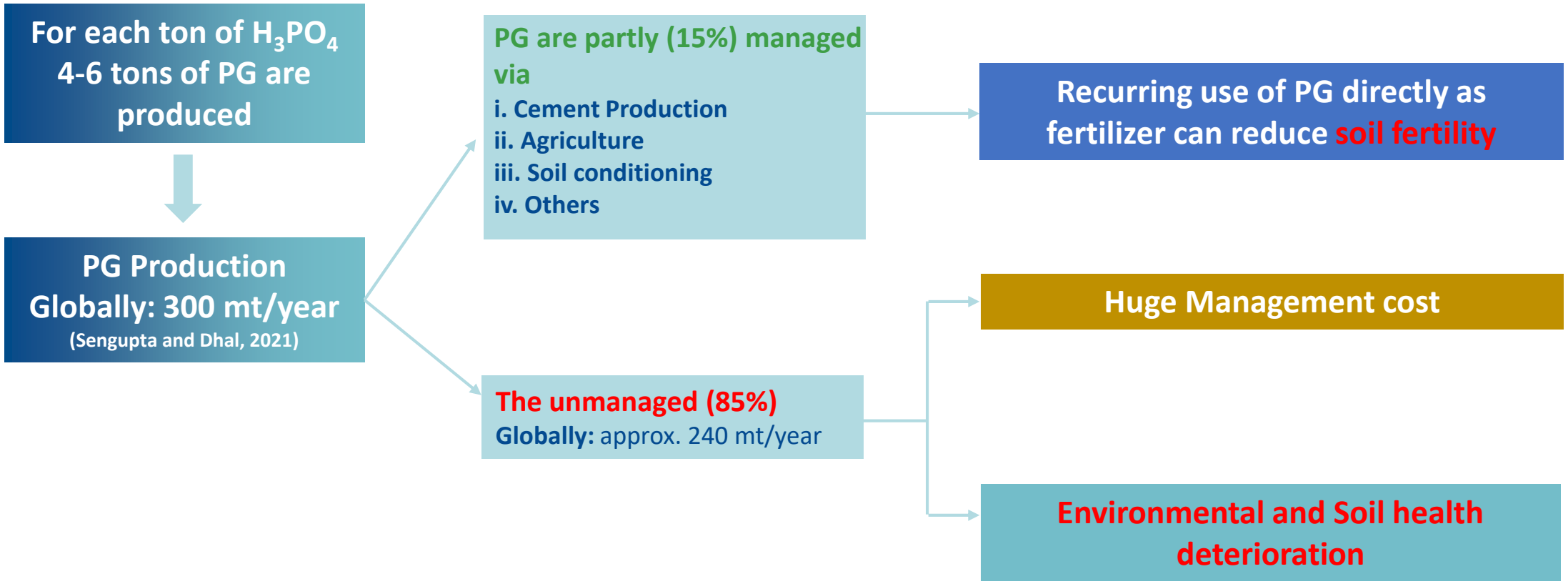
Phosphogypsum: Its Role and Importance in the Phosphoric Acid Industry

Phosphogypsum (PG: $CaSO_4 \cdot 2H_2O$) is a bulk industrial solid waste of "wet process" phosphoric acid production



Phosphogypsum annual production in several countries

Country	production (million tons/year)	Reference (Awad et al 2024)
China	22.0–75.0	Yang et al. 2016; Sun et al. 2022
USA	30.0–50.0	Wędrychowicz et al. 2019; Liang et al. 2017
Morocco	14.0–15.0	Ennaciri et al. 2020a
Russia	14.0	Lutskiy et al. 2018
Tunisia	10.0–12.0	Garbaya et al. 2021; Samet et al. 2019; Lassaad and Kammoun 2021; Zmemla et al. 2022
India	5.0–12.0	Naresha et al. 2016; Filho et al. 2023; Havanagi et al. 2018; Karim et al. 2021; Palla et al. 2022
South Korea	11.0	Rychkov et al. 2018
Ukraine	10.0	Thakur et al. 2023
Brazil	5.6–10.0	Thakur et al. 2023; Andrade Neto et al. 2021; Nisti et al. 2014
The Netherlands	4.0	Bituh et al. 2021
Spain	3.0	Pérez-López et al. 2010
Turkey	3.0	Değirmenci 2008; Türkel and Aksin 2012
Jordan	3.0	Al-Hwaiti et al. 2005
Poland	1.5–2.5	Wędrychowicz et al. 2019; Folek et al. 2011
Vietnam	1.2	Ngo et al. 2022
Algeria	1.0	Chaalal et al. 2020

Phosphogypsum: Its Potential Detrimental Role in Environment and Agriculture

Direct and recurring use of PG as fertilizer can reduce soil fertility

I. Heavy Metal Accumulation:

II. Soil pH Imbalance:

III. Nutrient Imbalance:

IV. Soil Microbial dysbiosis

Environmental and Soil health deterioration

I. Radioactivity:

II. Heavy Metals:

III. Eutrophication:

IV. Air Emissions:

V. Soil Microbial dysbiosis

Huge financial cost:

I. Storage and Handling ($5 to $10 per ton)

II. Environmental Monitoring ($1 to $2 per ton)

III. Remediation and Disposal ($20 to $30 per ton)

Phosphogypsum management approaches

- **Chemical Approaches**

✓Neutralization

✓Sulfur Recovery

✓Phosphorus Recovery

✓Rare Earth Elements (REEs) Extraction

✓Carbonation

✓Roasting

✓Microwave Heating

✓Recrystallization

- **Mechanical Approaches**

✓Stacking

✓Grinding

✓Compaction

✓Pelletization

Disadvantages of Chemical and Mechanical Management Process

- **Environmental Impact:**

  I. The potential for soil and water contamination, if not managed properly.

  II. Toxic secondary by-product.

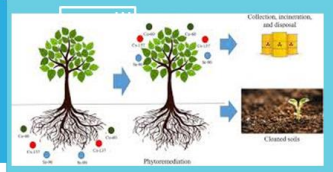
  (2016 stack failure in Florida led to a sinkhole that released over 200 million gallons of contaminated water into the Floridan Aquifer)

- **Costly:** Many of these methods are expensive and may not be economically feasible for all regions or industries (approx. $20 to $50 per ton of PG).
- **Safety:** Handling and processing PG can pose health and safety risks to workers, especially when dealing with hazardous chemicals or fine particles.
- **Time:** Some of these process are slow and time taking process (Weeks to years)

Green and Sustainable management approaches (Available)

3 Phytoremediation

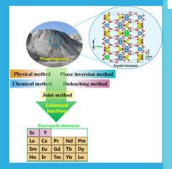
Hyper accumulator Plants:



Bioleaching 2

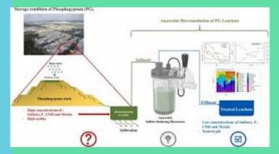
Aspergillus niger **Acidophilic Bacteria**

Sulfur Oxidizing Bacteria:
Acidithiobacillus thiooxidans



4 Anaerobic Digestion

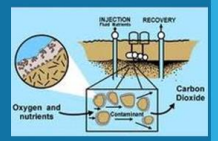
Methanogenic Bacteria



Bioremediation 1

I. **Sulfate-Reducing Bacteria (SRB)**

II. **Aerobic Fungi**



Problem with the current biotechnological Phosphogypsum management approaches

Time-Consuming

SRB mediated anaerobic Bioremediation processes are slow.

Complexity and Cost

Complex and expensive, thus often require specialized equipment and trained personnel

Environmental Conditions

Microbial Viability and Activity varied with environmental conditions

Potential for Secondary Pollution

Secondary pollution or disrupt local ecosystems.

Regulatory and Public Acceptance

regulatory hurdles and public resistance to the use of organisms

Solution: Indigenous Microorganisms (IMO) based Technology

to evaluate the feasibility of the biostimulation based aerobic biotransformation of PG using the indigenous microorganism

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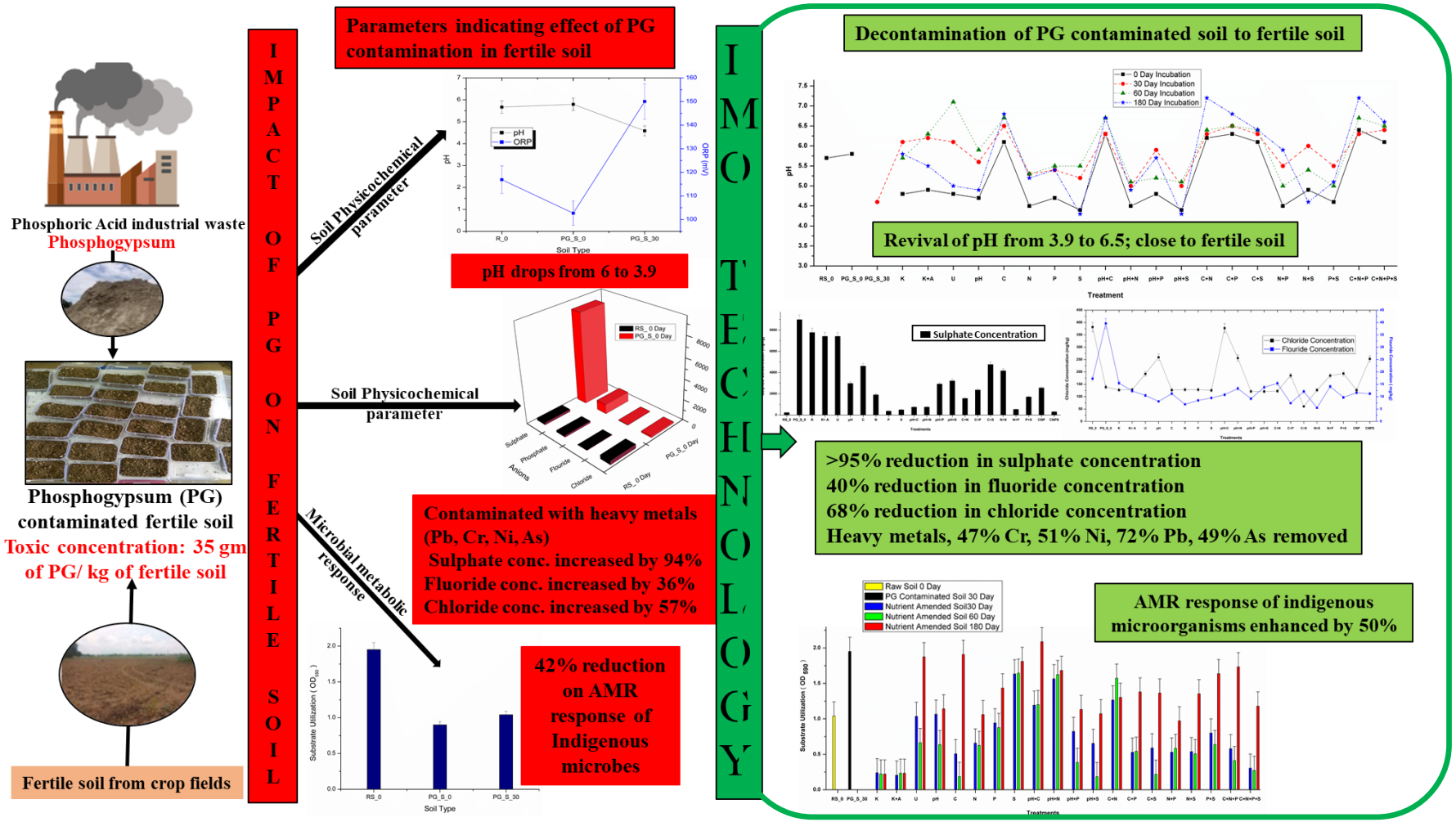
Summary of the work



Plan of work: Microcosm

Microcosm setup Experiment

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Physiochemical parameter analysis of PG and PG amended soil samples

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Anion and other mineralogical analysis PG and PG amended soil samples

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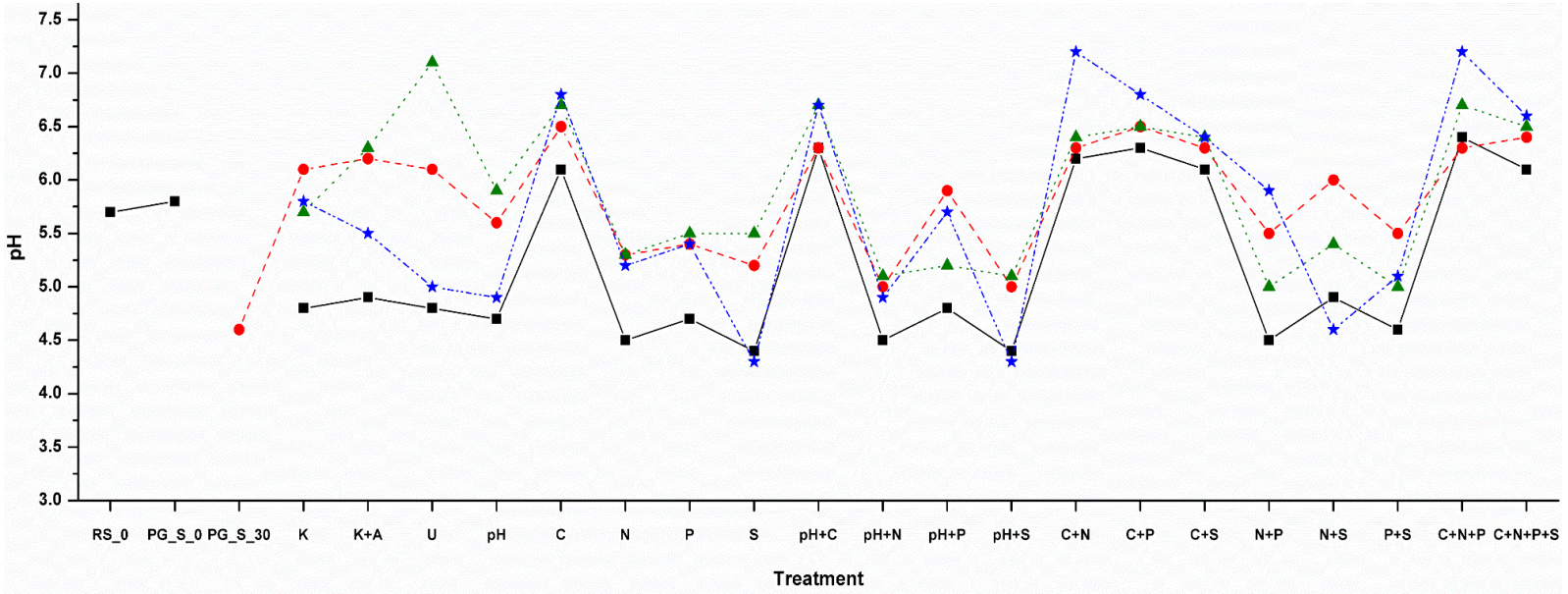
Community Level Microbial profiling of PG and PG amended soil samples

Microcosom Designation	pH with $NaHCO_3$	Acetate as carbon and electron acceptor	$NaNO_3$ as N sources	K_2HPO_4 as phosphate sources	Tween 80 as surfactant
K					
U					
pH	■				
C		■			
N			■		
P				■	
S					■
pHC	■	■			
pHN	■		■		
pHP	■			■	
pHS	■				■
CN		■	■		
CP		■		■	
CS		■			■
NP			■	■	
NS			■		■
PS				■	■
pHNPS	■	■	■	■	■

1. K: Killed control
2. U: Un-amendment
3. pH: pH Neutralization
4. N: Nitrogen
5. C: Carbon
6. P: Phosphate
7. S: Surfactant amendment
8. pH+C: pH with Carbon
9. pH+N: pH with Nitrogen
10. pH+P: pH with Phosphate
11. pH+S: pH with Surfactant
12. C+N: Carbon and Nitrogen
13. C+P: Carbon and Phosphate
14. C+S: Carbon and Surfactant
15. N+P: Nitrogen and Phosphate
16. N+S: Nitrogen and Surfactant
17. P+S: Phosphate and Surfactant
18. C+N+P: Carbon, Nitrogen and Phosphate
19. C+N+P+S: Carbon, Nitrogen, Phosphate and Surfactant

Result: pH neutralization

Among all the microcosm sets pH of carbon amended samples (C, pH + C, C + N, C + P, C + S, CNP and CNPS) was significantly higher ($p < 0.001$) than the control sets during 180 day of incubation.



- **Revival of pH from 3.9 to 7.1; close to fertile soil**

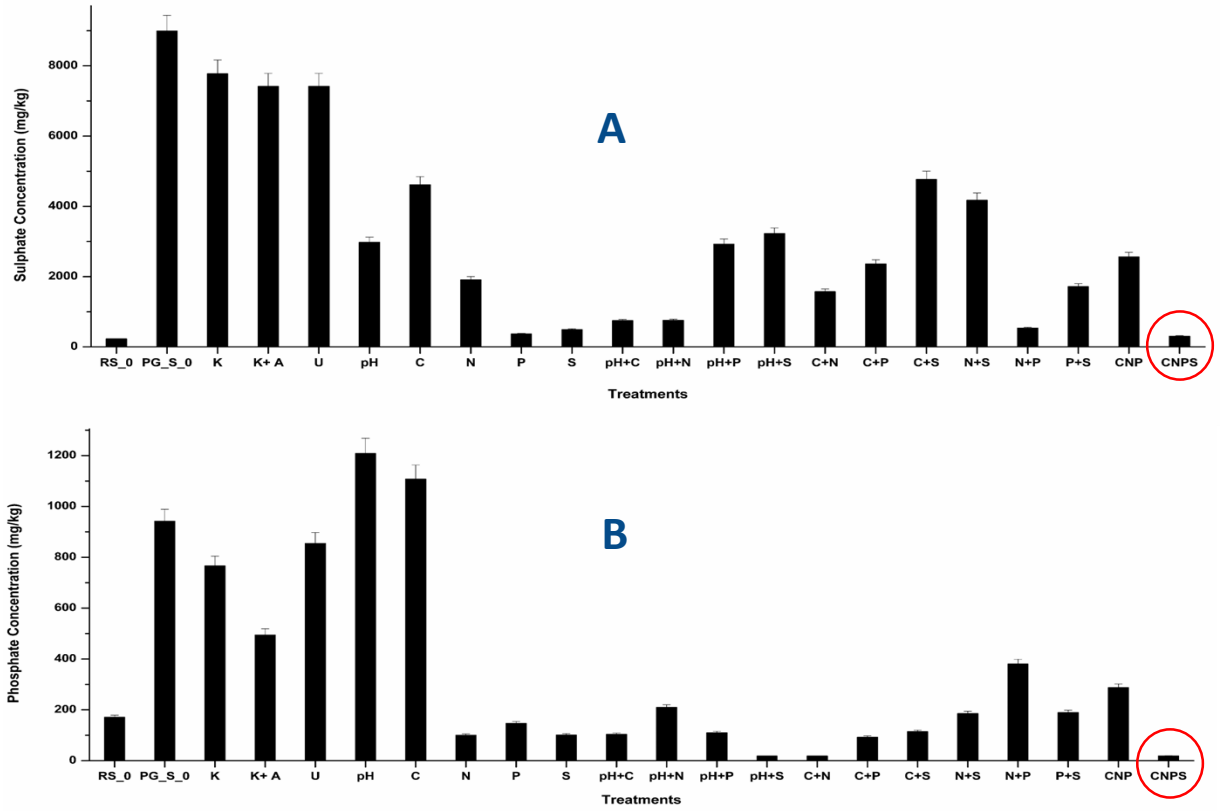
Effect of pH of 22 different nutrient amendments on PG contaminated soil samples of 180 days

Result: Sulphate and Phosphate reduction

Sulfate and phosphate concentration was significantly reduced ($p < 0.001$) in the CNPS microcosm set compared to PG contaminated soil in 180 days.

- **>95% reduction in sulphate concentration.**
- **> 96% reduction in phosphate concentration.**

C + N + P + S: Carbon, Nitrogen, Phosphate and Surfactant amendment

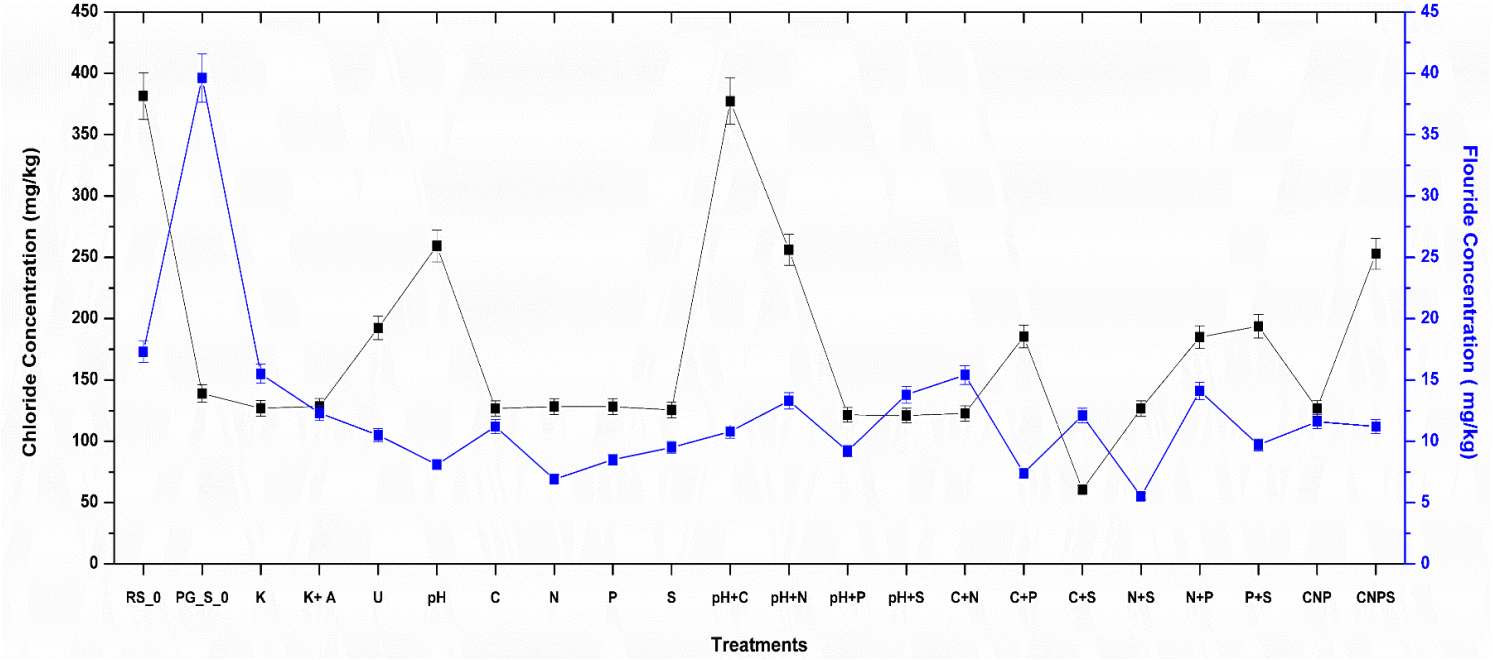


(A) Sulfate reduction profile, (B) Phosphate reduction profile, in microcosms over 180 days incubation period.

Result: Fluoride and chloride reduction

Fluoride and chloride concentration revealed an overall reduction in all the amended samples with respect to PG contaminated soil, although their values varied significantly among the treatments

- **40% reduction in chloride concentration**
- **68% reduction in fluoride concentration**

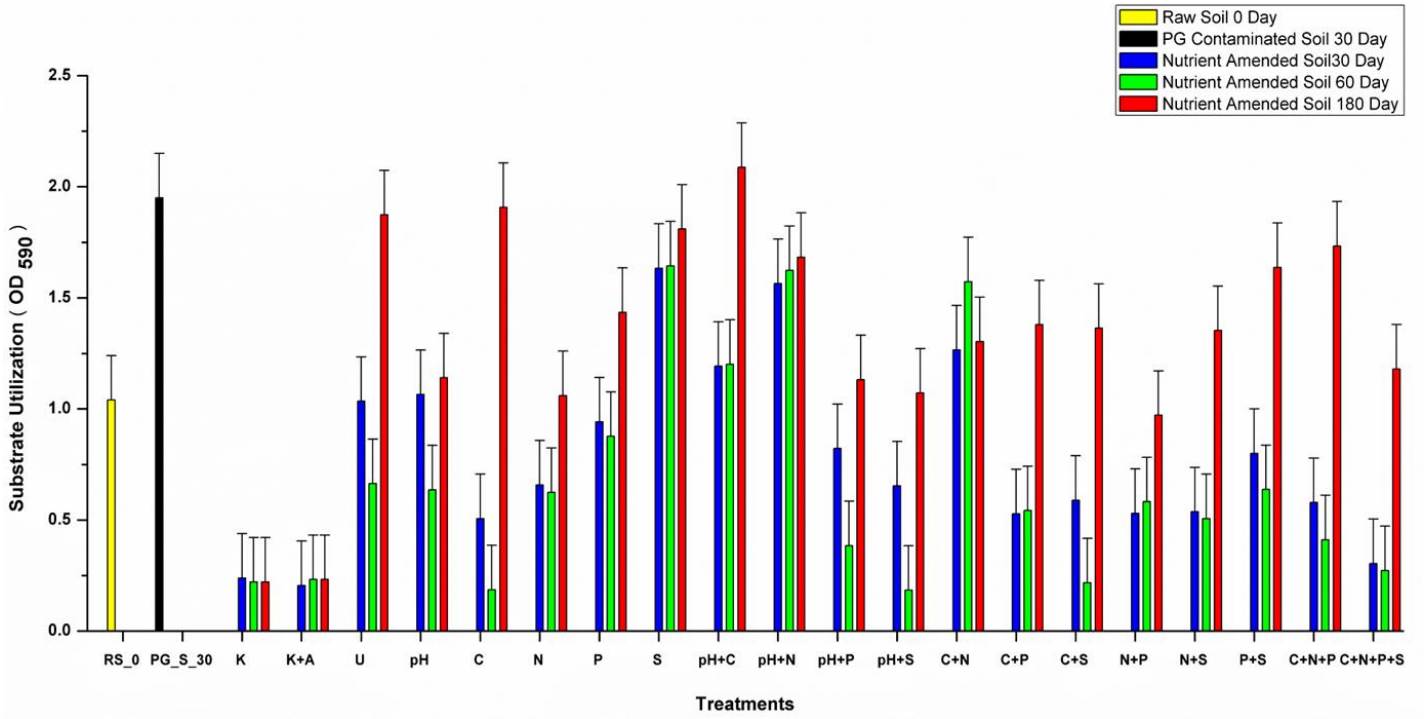


Anion distribution plot of nutrient amendment treated samples over 180 days incubation period.

Result: Microbial physiological profile

The substrate utilization response of C and S amended population (individually or in combination) was significantly enhanced in compare to control.

- **AMR response of indigenous microorganisms enhanced by 75%**



Community level physiological profile of nutrient amendment treated samples over 180 days incubation period.

Summary

Our (IMO) technology successfully recover the contaminated soil close to fertile soil by neutralizing soil pH (pH: 3.9 to 7.1), reducing anions, sulphate and phosphate concentration and by promoting the metabolic activity (75% enhancement in average metabolic rate) of the indigenous microorganisms.

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Impact of elevated phosphogypsum on soil fertility and its aerobic biotransformation through indigenous microorganisms (*IMO's*) based technology

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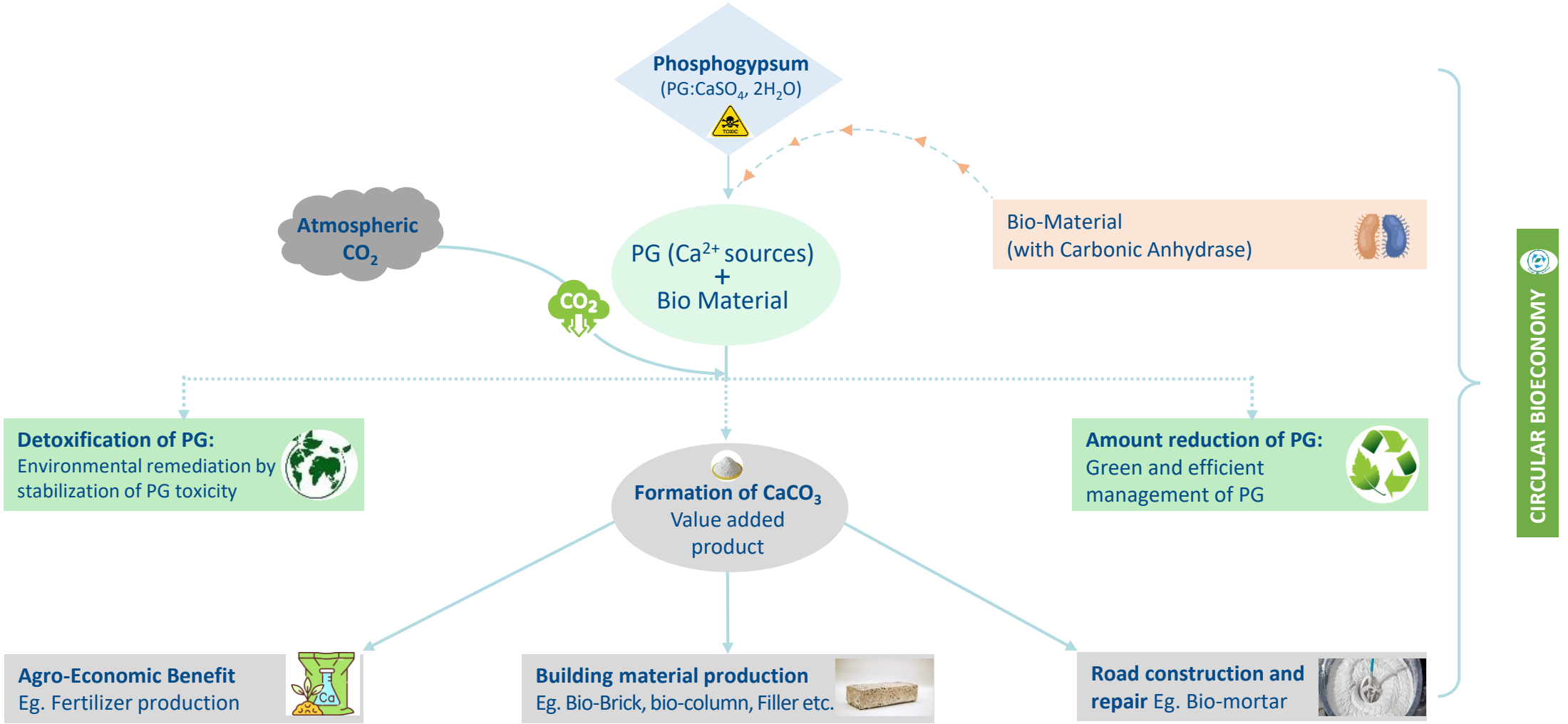
Microbial Induced Calcium Carbonate Precipitation (MICP)



SDG and MICP


14 LIFE BELOW WATER
SUSTAINABLE DEVELOPMENT GOALS
15 LIFE ON LAND
7 AFFORDABLE AND CLEAN ENERGY
3 GOOD HEALTH AND WELL-BEING
Water Pollution
Heavy Metal Removal
Solid Waste Disposal
Contaminated soil remediation
Geothermal Energy Utilization
Soil Thermal Conductivity
Sustainable Engineering Technology
MICP
Airborne Pollution
Fugitive Dust control
13 CLIMATE ACTION
Global Warming Control
Carbon Capture and Storage
Water Resource Conservation
Leakage Mitigation
6 CLEAN WATER AND SANITATION
Structural Autogenous Rehabilitation
Self-healing Materials
Disaster Alleviation
Soil Liquefaction Resistance
Building Material Recycling
Composite / Bio-materials
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Problems
Challenges

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