AGeo-Purifier — Integrated Field System for Carbon, Soil, and Microplastics in Precision Agriculture

(PMMB-ERW-Ca + Purifying Rotor (Ag))

Field-Adaptive Carbon Capture and Microplastic Remediation with AI Soil Sensing

Concept/Theoretical (TT) — v0.1 | Intended Repository: Zenodo
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Abstract (≤180 words)

We propose an integrated, field-deployable concept that couples **Enhanced Rock Weathering (ERW)** with **PMMB (Pollen-Microbiome Media & Biofilms)**, **waste-calcium alkalinity sources** (eggshell/calcium carbonate fines/CRC), **biochar sorption layers**, and an **AI-enabled Purifying Rotor** mounted on agricultural vehicles. The system performs three concurrent functions: (1) accelerates inorganic carbon capture via alkalinity (HCO_3^-/CO_3^{2-}) driven by Ca–Mg release and microbially enhanced silicate dissolution; (2) increases stable soil organic carbon via PMMB-biofilm micro-aggregates and biochar scaffolds; (3) removes microplastics and tyre-wear particles from service tracks through in-motion filtration in the wheel module. A front **Soil-Sense Bar** (NIR + EC + point pH) guides **variable-rate dosing** of basalt\:calcite and triggers rotor operating modes. A lightweight MRV protocol logs alkalinity/DIC in runoff, soil pH/Si, EC, and captured microplastics mass, producing per-hectare tCO_2 and g-MPs metrics.

What's new: a unified, farm-scale architecture that merges ERW + PMMB + Ca-waste alkalinity + biochar + in-motion MP capture and AI-guided variable dosing on the same vehicle, with a single MRV ledger. This is positioned as a Concept/Theoretical framework with a practical pilot plan.

Keywords: Enhanced Rock Weathering, PMMB, biochar, eggshell calcium, CRC fines, microplastics, tyre wear, variable-rate dosing, MRV, precision agriculture.

TL;DR (What's new here)

1. **Unified stack:** We combine five things in one farm workflow: basalt-based Enhanced Rock Weathering (ERW), **PMMB biofilms** (pollen-microbiome media), **recycled calcium** (eggshell/CRC fines), **biochar**, and **wheel-mounted microplastics capture**—all guided by AI.

2. **AI-guided variable dosing (VRD):** Real-time soil maps (pH/EC/NIR) tell the system exactly **where** to drop a tiny mix of basalt+calcite.
3. **Triple-duty wheel module:** The rotor both filters microplastics from tracks and increases rock-water contact at the soil surface, supporting faster weathering.
4. **One MRV ledger:** We log climate impact (tCO_2/ha from ERW) **and** cleanliness (g-MPs/ha captured) together, so results are auditable.
5. **Waste-to-value calcium:** We prefer eggshells/industrial fines over freshly calcined lime, to keep the climate balance positive.

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0. Evidence Map & Headline Predictions (for v1.0)

ERW yield (basalt on cropland): 1–4 tCO_2·ha^{-1}·yr^{-1} (climate/soil dependent; dose 10–40 t·ha^{-1} over season; bicarbonate export as primary sink).
SOC uplift (PMMB + biochar): +20–40% in micro-aggregate-protected pools over 1–3 seasons (bench→field trajectory).
MPs capture (APR wheel module): 0.5–2.0 kg MPs/TWP·ha^{-1}·yr^{-1} on service tracks (site-dependent traffic/soil).
VRD efficiency gain: ≥+15% input efficiency vs. uniform spreading (target: same CDR with less material).
pH mapping accuracy: RMSE ≤0.3–0.4 after local calibration (NIR+EC+periodic micro-probe).
Safety/LCA guardrail: recycled Ca (eggshell/CRC fines); dust-control; metals screen if olivine used.

> These are **targets** for pilots; cite field ERW studies for the 1–4 tCO_2 band and precision-ag literature for VR efficacy in the camera-ready version.

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1. Background & Rationale (for first-time readers)

What problem are we solving? Farms need practical ways to remove CO_2 from the air (climate) and microplastics from soils (cleanliness), **without** adding heavy cost or new trips over the field.

Our idea in one sentence: use the tractor you already drive to (a) spread a tiny, smart dose of reactive rock powder that locks CO_2 as dissolved bicarbonate/carbonate, (b) grow helpful biofilms that stabilize soil carbon, and (c) **collect microplastics while you move**—all measured in one logbook.

Key ingredients, in plain language:

- **Enhanced Rock Weathering (ERW):** Finely ground **basalt** naturally reacts with CO_2 in rainwater and makes the water slightly more alkaline; the carbon is carried away as dissolved bicarbonate. This is a slow natural process that we gently speed up.
- **PMMB biofilms:** We add **pollen-based scaffolds** plus a friendly microbiome. The biofilm hugs rock grains, releases gentle organic acids, and helps dissolve minerals that release calcium/magnesium—fuel for making bicarbonate.
- **Recycled calcium (eggshells/CRC fines):** Mild, local pH boost and extra alkalinity, but from **waste** sources so the climate math stays positive.

- **Biochar:** A porous charcoal that holds water and nutrients, gives the biofilm a "home," and helps trap microplastics in the filter.
- **Ag-Purifying Rotor (APR):** A wheel module on the tractor that uses motion-driven airflow and a small filter to collect microplastics and tyre-wear particles from farm tracks.
- **AI soil sensing:** A short bar at the front reads soil color/infrared, electrical conductivity and moisture, and sometimes pokes a tiny pH probe; then a small model on the tractor decides **where** to drop a dose.

Why it matters: This puts climate action, soil health and plastic cleanup **into the same pass**, with measurements that farmers and reviewers can follow.

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2. System Overview (step-by-step)

Platform: Agricultural tractor with front **Soil-Sense Bar** and wheel-integrated **Ag-Purifying Rotor (APR)**; onboard **ERW Hopper** with **Variable-Rate Dosing (VRD)** gate for basalt:calcite mix.

2.1 Soil-Sense Bar (front) - NIR/mini-hyperspectral reflectance for soil pH proxies, canopy/cover detection. - **NIR + Raman microplastics sensing (pilot):** inline spectral flag for MPs polymers (PE/PP/PS/PET) at surface; used to adapt APR capture mode. - **Microfluidic pH sensor (continuous):** low-flow micro-channel with optical pH dye for near-continuous mapping without frequent probe dips. - **GPR (ground-penetrating radar):** shallow subsurface structure (moisture lenses, compaction, root density proxies) to inform dosing/irrigation depth. - EC + volumetric moisture; temperature. - Point pH micro-probe "dip" at intervals for ground-truth. - GNSS/IMU for geo-registration (1–2 m grids).

2.1.1 Digital Agronomist (predictive layer) - **Weather-aware scheduler:** links to 24–72 h forecasts; if acidic hotspot + rain in ≤24 h → pre-rain basalt:calcite micro-dose to maximize weathering response. - **Look-ahead control:** combines GPR strata + soil sensors to recommend **irrigation pulse depth/length** post-dose only in treated cells. - **Advisories:** suggests pH recalibration frequency, brush/tine intensity, and APR suction set-points by soil state.

2.1.2 Physics-informed calibration (Soil-Sense 2.0) - **Field matrix:** 30–50 ground-truth points per field (NIR/EC/moisture ↔ lab pH-slurry). Weekly **drift-check** set of 6–8 points across moisture spectrum. - **Targets:** pH RMSE $\leq$ 0.3–0.4; confidence flag **pH_confidence < τ ⇒ VRD-OFF** for that cell. - **GPR shallow pass:** map compaction/moisture lenses; parameterize **pulse-irrigation depth** per micro-zone. - **Raman-MPs (pilot):** when surface MP signal is strong, the **APR set-point** (suction/ESP) is increased in that grid during the pass.

2.2 Ag-Purifying Rotor (APR) (wheel module) - Motion-harvested, Venturi-driven airflow; optional ESP-Lite bias. - **Soil-scrubbing brush (gentle):** rotating soft bristles lift thin MP films/crusts to restore water–rock contact area. - **Vibrating tines (micro-injection):** shallow (≤10–20 mm) agitation to lightly **embed** basalt:calcite fines into topsoil on acidic hotspots, improving contact and reducing drift. - **Media cartridge as "bioreactor-on-wheel" (PCore-Ag):** maintains live PMMB consortium (semi-closed humidification, micro-nutrient trickle). **No live release** via exhaust; injections only at AI-selected low-activity zones via tines. - **LS-APR particle path (low-speed ready):** (1) **Soft brush / lift belt** raises MP crust; (2) **Swirl-settler (low-ΔP vortex)** drops coarse dust; (3) **Sealed pocket** stores fines; (4) **ESP-Lite μA polish** on PCore media. No fan required. - **Anti-caking cassette:** safety **ΔP windows** with inertial back-flush pulses on acceleration/

braking; dust retained in inner pocket. - **Ground-scoop assists:** wide inlets A_in ≈ 40–60 cm^2 for gentle co-flow (not cyclone feed). **ΔP design:** 50–120 Pa @ Q = 5–15 $m^3 \cdot h^{-1}$ ⇒ P ≈ 0.03–0.5 W within harvested energy. - **Seed-impactor (optional):** adjustable impact grid to **damage weed seeds** captured on tracks (chemical-free suppression); **bypass** in off-target conditions.

2.3 ERW Hopper + VRD Gate - Basalt:calcite (typ. 3–5:1) dosing only at acidic hotspots (pH <6.2–6.5). - Optional biochar co-dose (1–3 t/ha equivalent over season).

2.3.1 VRD dosing logic & quick math - **Rain interval rule:** if forecast rain ≤ 24 h → issue **pre-rain micro-dose** in hotspot cells. - **Line-dose thumb rule:** ($1\ t \cdot ha^{-1} = 0.1\ kg \cdot m^{-2}$). For a spreader of width **W (m)**, mass per **meter** is **m_line = 0.1·D·W** ($kg \cdot m^{-1}$), where **D** is the field dose in $t \cdot ha^{-1}$. - **Example:** D = 20 $t \cdot ha^{-1}$, W = 0.5 m ⇒ **1.0 $kg \cdot m^{-1}$** in treated strips. Use VRD to **reduce treated length/area**, not the **$kg \cdot m^{-1}$**. - **Pulse-irrigation:** after dosing a cell, apply a short irrigation pulse at depth set by **GPR**; aim to boost HCO_3^-/ DIC formation without runoff.

2.4 Edge AI + Cloud MRV - On-edge TinyML fuses NIR/EC/pH, flags hotspots, commands VRD, and toggles APR modes. - Cloud aggregates passes → maps pH, ΔTA/DIC in runoff (if sampled), tCO_2/ha (ERW/ECW), g-MPs/ha, SOC proxies.

2.5 Module × KPI Table (v1.0) | Module | Primary function | KPI target (v1.0) | Notes | |---|---|---|---| | ERW + Ca (basalt + recycled Ca) | Alkalinity-driven C capture | **1–4 $tCO_2 \cdot ha^{-1} \cdot yr^{-1}$** | Bicarbonate export; dose 10–40 $t \cdot ha^{-1}$ | | PMMB + Biochar | SOC stability via micro-aggregates | **+20–40% SOC (protected pools)** | EPS/occlusion; POXC as early proxy | | APR (wheel) | MPs/TWP removal on tracks | **0.5–2.0 kg $MPs \cdot ha^{-1} \cdot yr^{-1}$** | Cyclone + media cartridge | | Soil-Sense Bar | VRD dosing accuracy | **pH RMSE ≤0.4**; VRD **≥+15%** efficiency | NIR+EC+micro-probe fusion |

2.6 Cost & ROI (illustrative placeholders) - **ERW material/ops:** ≈ **$100·$ha^{-1}$** (dose & fineness dependent).
- **Credits/benefit proxy: $200·$ha^{-1} \cdot yr^{-1}$** (CDR @ $50·$tCO_2^{-1}$ at 1–4 tCO_2 band + agronomic gains).
- **Gate:** deploy if payback ≤2 seasons; refine per site in Appendix CSV.

2.7 Diagram (to add in camera-ready) Schematic of tractor with **Soil-Sense Bar** (incl. GPR) → **Digital Agronomist** (forecast + scheduler) → **Edge-Box** → **VRD Gate** → **APR module** (cyclone + media/bioreactor + brush/tines) with arrows for data/flows and **irrigation controller** hook.

2.8 Farm-System Integration - **Irrigation pulses:** after localized dosing, trigger a short, cell-targeted irrigation pulse (depth from GPR strata) to initiate weathering; skip if rain imminent. - **On-farm circulars:** integrate **eggshell grinding** (from poultry) into recycled-Ca stream; feed **biochar** from crop residues into the media/hopper; log volumes in MRV. - **OPS loop:** Edge-Box exposes API to farm SCADA; safety locks to avoid over-wetting and off-target dosing.

2.9 Bark-Algorithm Soil Texturing (BAST) *Bio-inspired surface geometry for routing water, fines, and microbiota*

Concept. Shape the **rake/tread/roller pattern** on service tracks and treated strips to **mimic bark micro-topography** parameters **R, A(θ), W** (roughness, anisotropy, wetness persistence). Aim: concentrate thin films of water and PMMB payloads into micro-infiltration lines, remove MP “sheaths,” and increase rock–water contact for ERW — analogous to stemflow routing around trunks. filecite turn2file0

Geometry mapping (field controls): - **R → amplitude/frequency:** rib height **h** = 6–15 mm; pitch **p** = 25–60 mm (soil- and tyre-safe window). Higher **R** ⇒ higher h / lower p. - **A(θ) → orientation bias:** grooves at **±θ = 15–35°** to travel axis to create directional micro-flow toward the centerline or to edge drains; alternate bands every 5–10 m to prevent rill formation. - **W → retention pockets:** add micro-cups (Ø 8–12 mm; depth 3–5 mm) at groove intersections in low-slope areas to extend wetness time.

Implements: - **BAST-roller:** segmented ribbed roller with **swivelable ringlets** (±40°) to set A(θ) per pass; quick-swap sleeves for h/p variants. - **BAST-harrow:** flexible tine rack with **phase-shift** across rows to emboss the micro-cups. - **BAST-tyre boots (optional):** clip-on tread plates for the APR wheel to maintain pattern at low speed.

Module × Effect × Constraint (targets): | Control | Expected effect | KPI | Guardrail | |---|---|---|---| | ↑R (h 10–15 mm, p 25–40 mm) | Water film capture; fines focusing | **I_enrich ↑**; **soluble Si ↑** | Avoid >15 mm on sandy slopes (rilling) | | A(θ)=20–30° | Directed routing to infiltration stripe | **E_sf-analog ≥2×** | Alternate orientation bands to avoid channels | | W pockets | Longer wetness near basalt grains | **ΔpH, ΔTA in runoff** | Skip in saline zones (EC spikes) |

2.9.1 Pattern selection logic (predictive) - **Slope & soil:** set **h/p** lower on sandy, sloped sections; raise **R** on loams/clays with low rill risk. - **Forecast hooks:** before rain, bias **A(θ)** toward vegetated edge strips; post-rain, flip orientation to speed drying. - **APR sync:** align brush & tine direction with current grooves; VRD boosts dose where **W pockets** persist > T_wet.

Pilot (add-on to §7): - 3 patterns (Low-R / Med-R / High-R) × 2 orientations (0° vs 25°) on 6 subplots (≥50×3 m). - Metrics: high-res DEM (drone/RTK) → roughness; **runoff TA/DIC**; **soluble Si**; **MPs on surface** before/after APR; **ERW dose retention** inside grooves. - Success gates: **ΔI_enrich ≥ +10%** vs flat control; **MPs surface load −20–40%** in 2–4 passes; no increase in rill/erosion (visual + sediment traps).

---|---|---|---| | ↑R (h 10–15 mm, p 25–40 mm) | Water film capture; fines focusing | **I_enrich ↑**; **soluble Si ↑** | Avoid >15 mm on sandy slopes (rilling) | | A(θ)=20–30° | Directed routing to infiltration stripe | **E_sf-analog ≥2×** | Alternate orientation bands to avoid channels | | W pockets | Longer wetness near basalt grains | **ΔpH, ΔTA in runoff** | Skip in saline zones (EC spikes) |

APR synergy. The **Soil-scrubbing brush** aligns with groove direction to peel MP films; **vibrating tines** follow grooves to micro-embed basalt:calcite; **Digital Agronomist** can flip orientation before rain to steer flow toward vegetated edge strips.

Pilot (add-on to §7): - 3 patterns (Low-R / Med-R / High-R) × 2 orientations (0° vs 25°) on 6 subplots (≥50×3 m). - Metrics: high-res DEM (drone/RTK) → roughness; **runoff TA/DIC**; **soluble Si**; **MPs on surface** before/after APR; **ERW dose retention** inside grooves. - Success gates: **ΔI_enrich ≥ +10%** vs flat control; **MPs surface load −20–40%** in 2–4 passes; no increase in rill/erosion (visual + sediment traps).

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3. How It Works (mechanisms)

- **Inorganic CDR:** Ca^{2+}/Mg^{2+} release + waste-Ca alkalinity → ↑TA, ↑DIC (HCO_3^-/CO_3^{2-}); PMMB biofilms maintain reactive micro-environments (ligands/H^+ cycling) that accelerate silicate weathering.
- **Organic C accrual:** EPS-mediated micro-aggregates + biochar scaffolds → SOC stabilization (silt-clay fraction binding; occlusion).
- **Microplastics removal:** wheel filtration removes MPs/TWP; reduced plastic coating around mineral grains restores water–rock contact area.

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4. Control Logic (Sense → Decide → Act)

- **Sense:** NIR + EC + moisture + temp + ΔP(APR) every 0.5–1.0 s; periodic pH dip.
- **Decide:** classify grid cells; if acidic and moist, schedule VRD basalt\:calcite micro-dose; if dust-rich, raise APR suction/ESP bias.
- **Act:** gate opens for X g/m; APR switches to "capture/clean"; log action with geo-tag.

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5. MRV: What we measure and how we report

Runoff/Drainage (if available): TA, DIC, Ca^{2+}/Mg^{2+}; compute inorganic CDR with background subtraction.
Soils: pH, EC, soluble Si, SOC, mineralogy (XRD/FTIR) pre/post season.
MPs/TWP: grams captured per pass (filter mass difference; ATR-FTIR ID on subsamples).
Outputs: per-hectare tCO_2 (ERW/ECW), g-MPs, ΔpH surface map, SOC change (if measured).
Data: ISOXML/GeoJSON grids (1–2 m), time-stamped actions and doses.

5.1 Data Fusion & Telemetry - LoRa/edge logs for APR state, suction ΔP, filter mass trends, dosing events.
- AI fusion combines soil grids + APR capture to forecast where MPs/fines hinder weathering; suggests cleaning intensity and dose tweaks.
- **Ledger:** single CSV pack for Zenodo (runs, grids, KPIs, QA/QC).

5.2 MRV ledger schema (single-season) - **Flow/Capture:** ΔP(APR), Q_est (derived), cassette Δm, OPC bins ≥ 0.3 μm, VRD events (g/m & geo-cell).
- **Inorganic CDR:** TA/DIC in runoff/drainage when accessible + Ca/Mg; **SOC:** POXC as early proxy; soil pH/Si/EC as per text.
- **Export:** ISOXML/GeoJSON raster 1–2 m + consolidated **CSV ledger** for the season (Zenodo-ready).

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6. LCA & Safety (practical notes)

- Prioritize recycled $CaCO_3$ (eggshells, fines, CRC) over freshly calcined lime.
- Validate trace metals if using olivine; basalt generally lower risk.
- Dust control (PPE, moist spreading); filter servicing (anti-caking backflush).
- Energy budget: leverage motion-harvest for APR; minimize grinding fineness subject to reactivity targets.

6.1 Safety & closed logistics - **Electronics:** IP67 enclosures; ESP-Lite operated in **no-ozone** envelope. - **Cassettes:** sealed handling; **zero-discharge** back-flush; closed disposal stream (pyrolysis/melting for metal concentration).
- **Materials:** Ca from recycled streams preferred; **olivine** only after metals screen.

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7. Pilot Plan (3–6 weeks → extendable)

7.1 Bench/CFD prep (1–2 weeks)
- CFD-lite of Venturi & dosing plume; cartridge pressure-drop curves (anti-caking windows).
- NIR→pH calibration set (30–50 points) + micro-probe truth.

7.2 Field blocks (minimum 1 ha, 6–8 weeks)
- Two comparable plots: **Control** vs **APR+Sense+VRD**.
- Dosing: basalt:calcite **20 t·ha^{-1} equivalent**, targeted only to hotspots across passes.
- Sampling (biweekly): runoff **TA/DIC/Ca+Mg**; soil **pH/Si/EC/SOC (POXC proxy)**; **MPs filter mass**; APR ΔP logs.
- KPIs: **RMSE pH ≤0.4**; dosing error **≤±10%**; MPs capture **5–20 g·ha^{-1}·pass**; modeled ERW **tCO_2·ha^{-1}** within expected bounds for dose/climate.

7.3 Reporting add-ons (2–3 pages camera-ready)
- Maps: pH before/after; dosing heatmap; APR capture density.
- Tables: Module×KPI (targets vs. results); cost & ROI worksheet.
- Methods: SOP snippets; QA/QC checklists; Zenodo data dictionary.

7.4 TRL gates & acceptance - **Bench (1–2 weeks):** VRC-lite for LS-APR; cassette ΔP-flow curves; Gate = ΔP 50–120 Pa @ target Q; ESP-Lite within no-ozone envelope.
- **Calibration:** NIR→pH 30–50 pts + drift/moisture checks; Gate = RMSE ≤ 0.4; **pH_confidence** online.
- **Field (≥1 ha, 6–8 wks):** VRD efficiency ≥ +15%; MPs 5–20 g·ha^{-1}·pass; ERW within 1–4 tCO_2·ha^{-1}·yr^{-1} scaled to dose/climate; **Serviceability:** cassette swap < 3 min; **Zero-discharge** confirmed by mass balance.

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8. Limitations & Open Questions (be honest)

- NIR→pH models require local calibration and may drift with moisture/crop cover.
- Seasonal hydrology governs TA/DIC detectability; drainage access improves MRV confidence.
- Grinding energy and supply chain logistics set the CDR economics; explore industrial by-product silicates.
- Filter loading dynamics under mud and straw—optimize cyclone and cartridge geometry.

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9. Bill of Materials (indicative)

- Soil-Sense Bar: NIR mini-hyperspectral module; **compact Raman (785–830 nm) head for MPs flag**; **microfluidic pH module** (optical dye); EC+moisture probe; RGB-NIR camera; GNSS/IMU; MCU (TinyML capable).
- APR module (per wheel): Venturi ducting, cyclone pre-separator, ESP-Lite electrodes (optional), **rotary soft brush**, **vibrating shallow tines**, media cartridge (biochar+PMMB+basalt), dust bag, EMU harvester, LoRa.
- ERW system: hopper, auger, VRD gate, level sensors.
- Edge box: MCU/SoC, power management, storage, comms.
- Consumables: basalt fines, recycled $CaCO_3$ (eggshell/CRC), biochar, PMMB media.

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10. Data & Reporting (Zenodo-ready)

- **On-edge:** 1–2 m rasters; actions/doses; APR state.
- **Cloud:** per-pass logs, seasonal MRV ledger; export as CSV + GeoJSON + README.
- **Appendix pack for v1.0:** ROI worksheet; KPI tables; CFD notes; diagram; references with DOIs.

10.1 Carbon+ Credit (concept)

- **Bundled impact unit** that combines: (a) **inorganic CDR** from ERW ($tCO_2 \cdot ha^{-1}$), (b) **SOC uplift** (ΔSOC, validated proxies), (c) **microplastics removal** ($g\ MPs \cdot ha^{-1}$), and (d) **soil health/biodiversity cues** from Color-Form corridors.
- **Premium positioning:** certificate represents **holistic ecological restoration**, not just CO_2; intended for impact buyers at a higher price band with transparent MRV.
- MRV ledger exports a verified statement for buyers; align with existing CDR protocols + local soil standards.

10.2 Zenodo Package Checklist (ready-to-upload)

- **Files:** main PDF, **CSV ledger**, **ROI worksheet (CSV)**, **GeoJSON grids** (optional), README.md.
- **Metadata:** title, authorship (Ido Margolin, M.L.A., Technion graduate), keywords, abstract (≤180 words), **Concept/Theoretical (TT)** tag, version v1.2-Ag, license (CC-BY 4.0 suggested).
- **Disclosure:** no live microbe release; safety/LCA notes; limitations.
- **Figure placeholders:** System diagram & BAST patterns (to be added next version).

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11. Ethical & Governance Notes

- Clear TT (Concept/Theoretical) labeling; transparent uncertainties; no over-claiming.
- Publish protocols and negative results; community-verifiable MRV.
- Safety: dust/PPE; recycled Ca sources; metal screens if olivine considered; no UV on carriageways.

12. Business & Partnerships (go-to-market)

- **CSA model:** consumers sponsor treated hectares and receive verified impact reports (tCO_2 captured; g MPs removed).
- **Supply partnerships:** egg producers (eggshell streams), construction recyclers (CRC fines) for low-cost Ca.
- **Academic validation:** collaborate with Wageningen, UC-Davis, etc., across soils/climates; publish SOPs and datasets.
- **Consortium build:** equipment OEM × sensing partner × carbon-credit provider.

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12. Acknowledgments

The concept builds on prior PMMB, biochar, ERW, and microplastics-capture discussions, integrating them into a cohesive precision-agriculture workflow. It also interfaces with **WMP (Worms–Microbiome–Pollen)** for soil recovery and with **Color-Form Ecology** for optical-corridor operations on farm roads (see §13).

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12. Glossary (quick primer)

ERW: Enhanced Rock Weathering — using ground silicate rocks (e.g., basalt) to capture CO_2 as dissolved bicarbonate/carbonate.
PMMB: Pollen-Microbiome Media & Biofilms — pollen-based scaffolds plus helpful microbes that form films on soil/rock.
Biochar: Porous carbon material used as soil amendment and sorbent.
CRC fines: Recycled concrete fines (calcium-rich by-product).
APR: Ag-Purifying Rotor — wheel module that filters dust/MPs and activates surface contact.
VRD: Variable-Rate Dosing — dropping small, targeted amounts only where needed.
MRV: Measurement, Reporting, Verification — how we track results.

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13. Extensions & Synergies (v1.0 hooks)

13.1 WMP (Worms–Microbiome–Pollen): Pair APR passes with WMP bands (vermi 2–6% w/w; PGPR; pollen/SECs) to raise aggregation/Ksat and SOC. Use Demeter-AI style loops for dose scheduling and safety gates (metals/ARGs).
13.2 Color-Form Agro-Corridors: Treat farm lanes/edges as **optical corridors** (UV side-bands off-carriageway; matte rails; anti-polarization surfaces). This reduces insect traps on tracks, helping APR filtration and pollinator safety.
13.3 WMP×APR×ERW fusion: Worm-cast aggregation protects SOC; APR removes MPs that might sheath rock grains; ERW proceeds with better water–rock contact.

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14. Social & Ecological Impact

- **Regenerative Agriculture Score:** composite index merging CDR, SOC, MPs, water retention, biodiversity cues (Color-Form) for field-level labeling.
- **Global pilots:** launch in East Africa / SE Asia with local operator training; adapt to smallholders.
- **Equity & access:** low-cost retrofits; open SOPs; shared data commons via Zenodo.

Appendix A — MRV Math (concise)

A1. Inorganic CDR from TA/DIC & cation balance

Let ΔTA ($mol \cdot m^{-3}$) be the alkalinity increase above background in runoff over volume V (m^3) from area A (ha). Approx. inorganic C captured per hectare:

C_DIC [$tCO_2 \cdot ha^{-1}$] ≈ (ΔTA · V / A) · α · 44 $g \cdot mol^{-1}$, where $\alpha \in [0.5,1]$ accounts for carbonate speciation/charge balance. Cross-check with cation export: n_Ca + n_Mg vs ΔTA.

A2. MPs removal (per hectare)

m_MPs = Δm_cassette − m_fines_est. Normalize by treated track area and passes → g $MPs \cdot ha^{-1}$.

A3. VRD material accounting

For line dose m_line = 0.1·D·W ($kg \cdot m^{-1}$), with treated length L_t: field mass M = m_line·L_t. Use VRD to minimize L_t for target CDR.

A4. pH model quality

Report RMSE, MAE; track pH_confidence and disable VRD when below threshold.

Appendix B — BOTE Power & Flow (LS-APR)

- **Wheel RPM:** RPM ≈ v/(2πr)·60. For r=0.6 m, v=2.22 $m \cdot s^{-1}$ → ~35 RPM.
- **Dynamic pressure:** $q = \frac{1}{2}\rho v^2$ with ρ≈1.2 $kg \cdot m^{-3}$ → q~1–5 Pa. Justifies low-ΔP design.
- **Power window:** Target ΔP 50–120 Pa at Q 5–15 $m^3 \cdot h^{-1}$ ⇒ P = ΔP·Q ≈ 0.03–0.5 W harvested.

Appendix C — ROI Worksheet (columns)

Field_ID, Area_ha, Dose_t_ha, Treated_area_pct, Material_cost_per_t, Ops_cost_per_ha, Credits_price_per_tCO2, CDR_tCO2_per_ha, MPs_kg_per_ha, Yield_gain_percent, Revenue_gain_per_ha, Total_cost_per_ha, Total_benefit_per_ha, Net_per_ha, Payback_seasons

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References (with DOIs)

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