# 1. Soil Health Metrics

## Soil Report

This table tracks changes in soil health indicators over time at Site A, comparing conditions before and after the implementation of **regenerative farming practices**.

### **🌱 Overview of Time Periods**

* **Before Regenerative Farming (Sep 24)**: Baseline data before any intervention.
* **After 2 Months of Regenerative Farming**: Early signs of change.
* **After More Than 6 Months**: Longer-term effects of regenerative practices.

### **🧪 Key Soil Health Indicators Explained**

|  |  |
| --- | --- |
| **Parameter** | **What It Tells Us** |
| **Soil Organic Matter (SOM)** | Indicates overall soil fertility and biological activity. Higher values = healthier soil. |
| **Soil Organic Carbon (SOC)** | Carbon stored in organic matter. Crucial for nutrient cycling and soil structure. |
| **SOC/SOM Ratio** | Shows how much of SOM is made up of carbon. Typically around 58%. |
| **Total Carbon (TC)** | Includes both organic and inorganic carbon. |
| **Cation Exchange Capacity (CEC)** | Soil’s ability to hold and exchange nutrients. Higher = better fertility. |
| **Total Nitrogen (TN)** | Essential nutrient for plant growth. |
| **Clay/Silt/Sand %** | Determines soil texture, which affects water retention, aeration, and root penetration. |
| **Soil Texture** | Classification based on particle size distribution (e.g., Sandy Clay Loam). |

### **📊 What the Data Shows**

#### **🟤 Before Regenerative Farming**

* SOM: 5.04% — decent, but not exceptional.
* TC: 4.16%
* Nitrogen: Very low (<0.10%)
* CEC, SOC, texture: Not measured.

#### **🌿 After 2 Months**

* Slight increase in SOM (up to 6.38% in AR2).
* TC also increased.
* AR2 shows a **notable jump in nitrogen** (0.33%) and TN (3300 mg/kg), suggesting early biological activity.
* Still missing SOC, CEC, and texture data.

#### **🌳 After More Than 6 Months**

* **SOM skyrockets** (up to 13.05% in ARR1(b)).
* SOC was measured for the first time, showing a consistent SOC/SOM ratio (~58%).
* **Total Carbon increases significantly**, indicating carbon sequestration.
* **CEC values around 34 mq/100g** — strong nutrient-holding capacity.
* Soil texture is consistently classified as **Sandy Clay Loam**, which is good for both drainage and nutrient retention.

### **🔍 Key Takeaways**

* Regenerative farming **dramatically improves soil health** over time.
* Increases in SOM, SOC, TC, and CEC suggest better fertility, structure, and resilience.
* Nitrogen levels also improve, supporting plant growth.
* Soil texture stabilises, indicating consistent physical improvements.

## Soil Quality Index

This table is a **soil health scoring system** that uses a **Soil Quality Index (SQI)** to rate the condition of a soil sample based on four key metrics.

### 1️⃣ The Scoring Rubric

The rubric defines **rating categories** for each **Soil Quality Metric (SQM)**:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Metric** | **Very Low (1)** | **Low (2)** | **Average (3)** | **High (4)** |
| **SOM** (Soil Organic Matter %) | <1% | 1–2% | 2–5% | >5% |
| **CEC** (Cation Exchange Capacity, meq/100g) | <10 | 10–15 | 15–40 | >40 |
| **TC** (Total Carbon %) | <3% | 3–4% | 4–9% | >9% |
| **TN** (Total Nitrogen %) | <0.1% | 0.1–0.3% | 0.3–0.6% | >0.6% |

Each category is assigned a **rating score** from 1 (very low) to 4 (high).

### 2️⃣ Your Soil Sample Evaluation

The measured values for your sample are:

|  |  |  |
| --- | --- | --- |
| **SQM** | **Value** | **Rating** |
| SOM | **10.64%** | 4 (High) |
| CEC | **34.64** | 3 (Average) |
| TC | **6.96%** | 3 (Average) |
| TN | **0.33%** | 3 (Average) |

### 3️⃣ Weighting & Scoring

* Each metric has an **equal weight** of **6.25** (out of 25 possible points per metric).
* **Score** = Rating × Weight.

|  |  |  |  |
| --- | --- | --- | --- |
| **Metric** | **Rating** | **Weight** | **Score** |
| SOM | 4 | 6.25 | 25.00 |
| CEC | 3 | 6.25 | 18.75 |
| TC | 3 | 6.25 | 18.75 |
| TN | 3 | 6.25 | 18.75 |

### 4️⃣ Soil Quality Index (SQI)

* **SQI** = Sum of all scores = **81.25** (out of 100).
* According to the rubric:
  + **<50** = Poor
  + **51–80** = Average
  + **81–100** = Good

Your soil falls into the **Good** category.

### 5️⃣ Interpretation

* **Strengths**: Very high **SOM** (10.64%) — excellent for fertility, water retention, and microbial life.
* **Moderate areas**: CEC, TC, and TN are in the **average** range — still healthy, but could be improved for maximum productivity.
* **Overall**: The soil is in **good condition** and already supports strong plant growth, but boosting nutrient-holding capacity (CEC) and nitrogen could push it toward an **excellent** rating.

## SQI Rubric Sources

### 1️⃣ Soil Organic Matter (SOM)

**Why the range exists:**

* According to [Michigan State University’s “Organic Matters” guide](https://www.canr.msu.edu/hrt/uploads/535/78622/Organic-Matters-figure-6pgs.pdf), mineral soils can have **very low SOM (<1%)**, **average (2–4%)**, or **high (>5%)** levels.
* SOM varies with soil type, climate, and management. Sandy soils in hot, dry climates tend to have less SOM, while clay-rich or well-managed soils can build much higher levels.
* The rubric’s breakpoints (<1%, 1–2%, 2–5%, >5%) reflect these natural ranges and the fact that **>5% is considered excellent** for most mineral soils.

**Significance to soil health:**

* SOM is the “foundation” of soil quality — it improves structure, water retention, nutrient storage, and supports microbial life.
* Higher SOM means better resilience to drought, erosion, and compaction, and more slow-release nutrients for plants.

### 2️⃣ Cation Exchange Capacity (CEC)

**Why the range exists:**

* [Oregon State University’s CEC guide](https://forages.oregonstate.edu/ssis/soils/characteristics/cec) explains that CEC measures the soil’s ability to hold positively charged nutrients (Ca²⁺, Mg²⁺, K⁺, etc.).
* Sandy soils with little clay or organic matter have **very low CEC (0–10)**, loams are **slightly low (10–15)**, clay-rich or organic soils are **adequate to high (15–40)**, and very heavy clay or organic soils can exceed **40**.
* The rubric’s cutoffs (<10, 10–15, 15–40, >40) align with these natural groupings.

**Significance to soil health:**

* Higher CEC means the soil can store more nutrients and buffer against leaching.
* Very high CEC (>40) can sometimes bind nutrients too tightly, reducing availability, but generally indicates rich, fertile soils.

### 3️⃣ Total Carbon (TC)

**Why the range exists:**

* [Landcare Research’s soil carbon guide](https://sindi.landcareresearch.co.nz/Content/HelpTotalC.html) notes that total carbon is a proxy for organic matter (SOM ≈ TC × 1.7).
* In mineral soils, <3% TC is low, 3–4% is modest, 4–9% is healthy, and >9% is exceptional — often found in organic-rich or peat soils.
* The rubric’s thresholds reflect these benchmarks.

**Significance to soil health:**

* Carbon is the backbone of organic matter, influencing **biological activity, nutrient cycling, and soil structure**.
* Higher TC means more energy for microbes, better aggregation, and greater water-holding capacity.

### 4️⃣ Total Nitrogen (TN)

**Why the range exists:**

* Nitrogen is a key plant nutrient, but natural levels vary widely.
* In most agricultural soils, <0.1% TN is very low, 0.1–0.3% is low, 0.3–0.6% is moderate, and >0.6% is high — often linked to high SOM or recent organic inputs.
* These ranges are consistent with agronomic research (including the one you linked to, which discusses nutrient thresholds in soil quality evaluation).

**Significance to soil health:**

* TN is essential for plant growth and is closely tied to SOM — soils with more organic matter generally have more nitrogen.
* Adequate TN supports vigorous crops, while low TN can limit productivity unless supplemented.

#### 📌 Putting It Together

Your rubric’s ranges are **not arbitrary** — they’re grounded in well-established soil science benchmarks:

* **SOM** → organic matter foundation for fertility and resilience.
* **CEC** → nutrient-holding capacity.
* **TC** → carbon store driving soil biology and structure.
* **TN** → nitrogen reserve for plant growth.

The ranges reflect **natural variability** across soil types and climates, and the thresholds mark transitions from poor → average → good → excellent soil function.

## Actionable Insights

### 1️⃣ Soil Organic Matter (SOM)

**If low (<5% in your rubric):**

* **Add organic amendments**: Apply well-composted manure, crop residues, or green manures to feed soil microbes and build humus.
* **Cover cropping**: Grow legumes, clovers, or multi-species mixes to add biomass and protect soil from erosion.
* **Reduce tillage**: Minimise soil disturbance to slow organic matter breakdown.
* **Mulching**: Use straw, wood chips, or plant residues to protect the surface and add carbon as they decompose.

**Why it works:** SOM is the backbone of soil health — it improves structure, water retention, and nutrient cycling.

### 2️⃣ Cation Exchange Capacity (CEC)

**If low (<15 meq/100g in your rubric):**

* **Increase organic matter**: Organic matter has a high CEC, so building SOM directly boosts nutrient-holding capacity.
* **Incorporate biochar**: Stable carbon with a high surface area can significantly raise CEC in sandy soils.
* **Clay addition (where feasible)**: In very sandy soils, adding fine-textured material (e.g., bentonite) can improve CEC, though this is more practical in small areas.
* **Balanced fertilisation**: Apply nutrients in smaller, more frequent doses to reduce leaching losses.

**Why it works:** CEC determines how well soil retains and supplies nutrients to plants — low CEC soils lose nutrients quickly.

### 3️⃣ Total Carbon (TC)

**If low (<4% in your rubric):**

* **Same strategies as SOM**: Since TC is largely derived from organic matter, building SOM will raise TC.
* **Perennial systems**: Plant deep-rooted perennials or agroforestry species to add stable carbon below the surface.
* **Residue retention**: Avoid burning or removing crop residues — keep them in the field to recycle carbon.

**Why it works:** Carbon fuels soil biology, improves aggregation, and supports long-term fertility.

### 4️⃣ Total Nitrogen (TN)

**If low (<0.3% in your rubric):**

* **Legume integration**: Grow nitrogen-fixing plants (e.g., beans, peas, clovers) in rotations or as cover crops.
* **Organic nitrogen sources**: Apply composted manure, poultry litter, or plant-based compost.
* **Reduce nitrogen losses**: Avoid over-irrigation and time nitrogen applications to crop demand to prevent leaching.
* **Microbial stimulation**: Maintain living roots year-round to support nitrogen-fixing microbes.

**Why it works:** Nitrogen is essential for plant growth, and in healthy soils, much of it comes from organic matter and biological fixation.

#### 🌿 Big Picture Strategy

If **multiple indicators are low**, the most efficient approach is to:

* **Adopt regenerative practices** that build SOM (which in turn improves CEC, TC, and TN).
* **Maintain continuous living cover** to protect and feed the soil.
* **Diversify plant species** to support a wide range of soil organisms.
* **Minimise chemical and mechanical disturbance** to preserve soil structure and biology.

## Case Study: Provided Data

Mapping **Site A “before and after regenerative farming” data** against the **Soil Quality Index (SQI) rubric thresholds**, this will show exactly where the farm started, where they are now, and which actions would have the biggest payoff if any metric dips below target in the future.

### 1. Mapping Your Data to the Rubric

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Time Period & Sample** | **SOM (%)** | **SOM Rating** | **CEC (meq/100g)** | **CEC Rating** | **TC (%)** | **TC Rating** | **TN (%)** | **TN Rating** | **SQI Score** | **Category** |
| **Before Regen (BR1)** | 5.04 | 4 (High) | n/d | — | 4.16 | 3 (Average) | <0.10 | 1 (Very Low) | — | — |
| **After 2 mo (AR1)** | 5.48 | 4 (High) | n/d | — | 4.46 | 3 (Average) | <0.10 | 1 (Very Low) | — | — |
| **After 2 mo (AR2)** | 6.38 | 4 (High) | n/d | — | 5.03 | 3 (Average) | 0.33 | 3 (Average) | — | — |
| **>6 mo (ARR1a)** | 9.43 | 4 (High) | 34.92 | 3 (Average) | 6.52 | 3 (Average) | n/d | — | — | — |
| **>6 mo (ARR1b)** | 13.05 | 4 (High) | 34.74 | 3 (Average) | 8.39 | 3 (Average) | n/d | — | — | — |
| **>6 mo (ARR2a)** | 7.71 | 4 (High) | 34.21 | 3 (Average) | 4.69 | 3 (Average) | n/d | — | — | — |
| **>6 mo (ARR2b)** | 12.38 | 4 (High) | 34.68 | 3 (Average) | 8.24 | 3 (Average) | n/d | — | — | — |

**n/d = no data**

### 2. What This Shows

* **SOM**: Already excellent (>5%) across all samples — regenerative farming clearly boosted it further, especially after 6 months.
* **CEC**: Consistently in the **average** range (15–40). This is good, but not exceptional — there’s room to push it above 40 for maximum nutrient-holding capacity.
* **TC**: Solidly in the **average** range (4–9%). Some samples are close to “high” (>9%), which would indicate exceptional carbon storage.
* **TN**: Initially very low (<0.10%), but AR2 jumped to **average** (0.33%). More data after 6 months would confirm if this improvement is sustained.

### 3. Targeted Recommendations if Metrics Fall Below Thresholds

|  |  |  |
| --- | --- | --- |
| **Metric** | **If Below Target** | **Key Actions** |
| **SOM** (<5%) | Add compost/manure, grow cover crops, reduce tillage, and keep soil covered year-round. |  |
| **CEC** (<15) | Build SOM, add biochar, diversify crop rotations, and avoid nutrient leaching. |  |
| **TC** (<4%) | Retain crop residues, integrate perennials, and avoid burning organic matter. |  |
| **TN** (<0.3%) | Plant legumes, apply organic N sources, time N applications to crop demand, and maintain living roots. |  |

### 4. Big Picture

The data shows **clear improvement** in SOM and TN within months of starting regenerative farming, with TC and CEC holding steady in the healthy range. The next frontier is **pushing CEC into the “high” category** and **locking in nitrogen gains** — both of which will happen naturally if the farm keeps building organic matter and diversifying plant cover.

# 2. Harvest Yield Records

## Dataset Description

### 1️⃣ Dataset Overview

#### 📌 Scope

* **Crops**:
  + *Limau Nipis* (Persian lime type) – harvested all year
  + *Limau Kasturi* (Calamansi) – also year-round
* **Farming Methods Compared**:
  + **Mar–Aug 2024**: 9 sites under **conventional farming**
  + **Sep 2024–Feb 2025**: 1 site switched to **regenerative farming**, remaining 8 stayed conventional
* **Metrics Recorded per Month**:
  + Grade A weight (kg) and Grade B weight (kg)
  + Total harvest weight (kg)
  + Low Grade Product Percentage (LGPP)
  + Revenue split by grade using a fixed price per kg
  + Revenue/Fertiliser Cost Margin ratio (proxy for profitability)

### 2️⃣ Key Observations

#### Limau Nipis

* **Total harvest jump** after switch to mixed system:
  + From **25,257 kg** (6-month total pre-switch) → **47,000 kg** post-switch (an **86% increase** overall).
* **Grade B volume** surged **4.2×** (3,470 kg → 14,677 kg).
* **LGPP**:
  + Conventional avg: **14%**
  + Mixed period avg: **28%** (doubling defect rate / low-grade share).
* **Revenue/Fertiliser Cost Margin** improved in many months post-switch despite higher LGPP, suggesting higher total output more than offset quality loss.

#### Limau Kasturi

* **Total harvest** also increased:
  + 29,117 kg pre-switch → 47,565 kg post-switch (**63% increase**).
* **Grade B**: 2,249 kg → 3,317 kg (modest increase, **1.47×**).
* **LGPP** remained very low: ~6% both before and after, with brief spikes (10–12%).
* **Revenue/Fertiliser Cost Margin** generally improved post-switch due to a yield boost.

### 3️⃣ Patterns in Low-Grade Products (LGPP)

* For **Limau Nipis**, the LGPP **almost always rises** after the regenerative site enters the dataset, from a steady ~11–20% to a persistent 23–45% monthly.
* For **Limau Kasturi**, LGPP did **not** show the same surge — it stayed low with rare bumps.

### 4️⃣ Plausible Factors Behind Higher Low-Grade Shares After Regenerative Farming

Given the dataset structure, the spike seems linked to the regenerative site’s first production cycle. Some likely factors:

|  |  |
| --- | --- |
| **Potential Factor** | **How It Could Increase LGPP** |
| **Transition shock** | Regenerative systems often require 1–3 seasons for soil microbiome and nutrient cycles to stabilise; early yields can have more variable fruit quality. |
| **Pest/disease adaptation** | Reduced synthetic pesticide use could initially increase pest pressure until predator–prey balance re-establishes, leading to more blemished or misshapen fruit. |
| **Nutrient release timing** | Organic or microalgae-based inputs release nutrients more slowly; early mismatch in fruit fill stages can affect size, colour, or skin quality. |
| **Weather/seasonal overlap** | Sep–Feb includes the wet season in Malaysia; excess rainfall may interact with regenerative soil practices (higher moisture retention) to cause rind splitting or fungal spots. |
| **Harvest management at a regenerative site** | Slightly looser grading standards in the transition period could increase recorded “B” grades if pickers are overcautious or fruit matures unevenly. |
| **Tree age/productivity cycle** | If the regenerative site’s trees were at a different maturity or flush stage, fruit uniformity might suffer short-term, even while total kg increases. |

### 5️⃣ Notable Contrasts Between Crops

* Limau Nipis appears **more sensitive** in LGPP to the transition — likely due to thinner skin and higher susceptibility to cosmetic defects.
* Limau Kasturi, with thicker skin and higher acidity, maintained LGPP levels despite method change, indicating crop-specific resilience.

## Actionable Insights

### 1️⃣ Fine‑Tune Nutrition Management

* **Synchronise nutrient release with fruiting stages** — Use a mix of fast‑release organic sources (e.g. fish amino acids, compost tea) during early fruit fill, with slower‑release compost and biofertilisers for baseline fertility.
* **Leaf and soil analysis** every 2–3 months to detect hidden deficiencies that affect size, colour or skin strength.
* **Adjust microalgae concentration or timing** if too much vegetative growth is delaying fruit ripening or leading to uneven maturity.

### 2️⃣ Targeted Pest & Disease Suppression

* **Integrated pest management (IPM)**: release beneficial insects early in the season, maintain flowering borders to sustain them year‑round.
* **Spot sprays** of bio‑pesticides (e.g. neem, Bt, potassium bicarbonate) only where pest pressure is detected — this avoids overuse but still keeps blemishes down.
* Monitor rind‑borer, mites, and fungal spotting closely in humid months.

### 3️⃣ Harvest & Grading Practices

* **Tighter harvest window** — picking slightly earlier (but not immature) can reduce drop and skin damage, especially in wet periods.
* **On‑site pre‑sorting** so low‑grades are separated before they influence storage quality of the good fruit.
* Train harvest crew to handle fruit gently and avoid stem punctures.

### 4️⃣ Climate & Water Management

* In the Malaysian wet season, **prune to improve airflow** and reduce fungal incidence.
* Use **mulch and drainage channels** to keep root zones drier during prolonged rain — excess moisture during fruiting increases splitting and blemishes.
* Split high‑volume microalgae or fertigation events into smaller, more frequent applications to avoid sudden surges in water and nutrient load.

### 5️⃣ Transition Strategy for Regenerative Plots

* **Staggered conversion** — switch a smaller section at first, to let predator–prey and soil nutrient cycles stabilise without affecting the full harvest.
* Trial **intercropping or cover crops** that deter pests and promote beneficial insect populations.
* Document LGPP, pest pressure, and weather alongside inputs to see which factor correlates most with defects.

For Limau Nipis in the transition period, combine regenerative inputs with **one or two critical‑point conventional interventions** (e.g., pre‑flower nutrient boost, post‑fruit‑set pest block). This hybrid approach often bridges the early‑cycle quality gap while the ecosystem balances itself.

# 

# 3. Cost Comparison

## Main Cost Analyses

This table is a **side‑by‑side cost comparison** between **Conventional Farming** and **Regenerative Farming** over a 6‑month period for a single site (Site A, 3 ares), including **itemised spending by date, category, and input type**.

### Summary of main figures

|  |  |  |  |
| --- | --- | --- | --- |
| **Farming method** | **Monthly average (RM)** | **6‑month total (RM)** | **Notes** |
| Conventional | 888.30 | 5,329.80 | Heavy recurring pesticide, foliar, and fertiliser inputs every ~3–6 days |
| Regenerative | 710.00 | 4,260.00 | Dominated by cost of microalgae water and reduced pesticide use |
| **Saving** | — | **1,069.80** | ~20% reduction in total costs |

### Structure

* **Conventional farming (before Sept 2024):**
  + Repeats a **high‑frequency spray and feed cycle**:
    - Pesticide + foliar agrochemicals ~RM 171 each time.
    - Fertiliser inputs alternating between NPK blends (RM 217.80) and organic fertiliser (RM 157.50).
  + Activities occur on roughly a 4–6 day interval.
  + Total cost: RM 5,329.80 in six months.
* **Regenerative farming (starting Sept 2024):**
  + **Main soil input**: 6,000 L of microalgae water each month (RM 600).
  + **Pesticides**: Still used, but far less frequently (2–3 times/month) and at a much lower per‑application cost (~RM 55).
  + No synthetic or bulk organic fertiliser listed.
  + Total cost: RM 4,260 in six months.

### Cost drivers

* **Conventional:** The frequent use of both chemical and organic fertilisers plus high‑cost pesticide/foliar mixes drives up spend.
* **Regenerative:** Microalgae water is the largest single cost item, but the reduced pesticide reliance and elimination of other fertilisers results in lower total expenditure.

### Key insights

* **Savings are consistent month‑to‑month** under regenerative practice due to a stable input schedule.
* **Labour implications:** Fewer input types and lower frequency in regenerative farming could also reduce labour and application complexity — a side benefit not monetised here.
* **Input substitution:** The shift is essentially from multiple fertilisers and foliar blends to a single regenerative agent plus minimal pesticide.
* **Sustainability impact:** Aside from cost, the regenerative method likely reduces nutrient runoff and synthetic chemical use.

## Math Checks

### 🧾 Cost Comparison Summary (6 Months)

|  |  |  |  |
| --- | --- | --- | --- |
| **Farming Method** | **Monthly Avg (RM)** | **Total Cost (RM)** | **Cost Reduction** |
| Conventional | RM 888.30 | RM 5,329.80 | — |
| Regenerative | RM 710.00 | RM 4,260.00 | ~20% (RM 1,069.80) |

* **Conventional**: Frequent use of synthetic fertilisers, organic fertilisers, and pesticide/foliar mixes.
* **Regenerative**: Dominated by monthly microalgae water applications and minimal pesticide use.

### 🧪 Input Volumes and Realism for 300 m² Plot

#### ✅ Pesticide/Foliar Sprays

* **Corrected unit**: 1000 ml (not 1000 L).
* **Tank mix volume**: 2 L per application.
* **Spray rate**:  
   [ \frac{2\ \text{L}}{300\ \text{m}^2} = 6.67\ \text{L/1000 m}^2 = 66.7\ \text{L/ha} ]
* **Verdict**: Realistic for low-volume spot spraying or directed foliar application.

#### ✅ Microalgae Water Application

* **Volume**: 6,000 L/month.
* **Rate**:  
   [ \frac{6000\ \text{L}}{300\ \text{m}^2} = 20\ \text{L/m}^2 = 200,000\ \text{L/ha/month} ]
* **Dry biomass concentration**: 1 g/L → 6 kg dry biomass/month.
* **Nutrient delivery estimate**:
  + **Nitrogen (7–10%)**: 0.42–0.60 kg/month → 2.5–3.6 kg over 6 months.
  + **Phosphorus (0.5–1.5%)**: 0.03–0.09 kg/month → 0.18–0.54 kg over 6 months.
* **Verdict**: Agronomically plausible for biostimulant use. Volume is high but manageable with hose or pump systems.

#### ✅ Fertiliser Application (Conventional)

* **Organic fertiliser**: 25 kg × 5 units = 125 kg per entry.
* **Rate per entry**:  
   [ \frac{125\ \text{kg}}{300\ \text{m}^2} = 416.7\ \text{kg/1000 m}^2 = 16.7\ \text{t/ha} ]
* **Cumulative over 4 entries**: 500 kg → 55.6 t/ha.
* **Verdict**: High but not implausible for intensive soil building. Nutrient analysis aligns with EP calculations.

### 🌍 Carbon and Eutrophication Impact Validation

#### ✅ Carbon Uptake by Microalgae

* **Uptake factor**: −1.83 kg CO₂eq/kg dry biomass (based on 50% carbon content).
* **Applied biomass**: 72 kg over 6 months.
* **Carbon footprint reduction**:  
   [ 72\ \text{kg} \times -1.83\ \text{kg CO₂eq/kg} = -131.76\ \text{kg CO₂eq} ]
* **Verdict**: Matches your calculated footprint. Uptake factor is scientifically valid.

#### ✅ Carbon Credit Revenue

* **Avoided emissions**: 987.1 kg CO₂eq/year = 0.9871 t/year.
* **Credit price**: RM 15/t → Revenue = RM 15/year.
* **Verdict**: Not economically viable at this scale or price. Carbon credits only become meaningful with larger volumes or higher market rates.

#### ✅ Phosphorus EP and Carbon Footprint

* **P applied (conventional)**: 74 kg/year.
* **Emission factor**: 0.05 → 3.7 kg P emitted.
* **Midpoint CF**: 0.100 → EP = 0.370 kg PO₄eq.
* **Carbon EF**: 3.125 kg CO₂eq/kg P → C footprint = 231.3 kg CO₂eq.
* **Regenerative P applied**: 0.4 kg/year → EP = 0.002 kg PO₄eq.
* **Verdict**: 99.5% reduction in eutrophication potential and carbon footprint — consistent with your nutrient substitution logic.

## 

## **Actionable Insights**

### Logistics on a 300 m² site

* **Microalgae water:** 6,000 L/month is one 6 m³ delivery or six 1 m³ IBC totes — fine with a hose/pump; impractical with knapsack sprayers.
* **Sprays:** A 15–20 L knapsack doing 2–3 fills per application matches the “2 L total mix” only if those lines reflect concentrate volumes, not spray output.
* **Storage/handling:** Ensure drainage capacity; 20 mm in one dose is okay on well‑structured soil, but split applications could reduce runoff risk.

### 💡 Why Split Microalgae Applications?

* **Hydrology and infiltration**
  + 6,000 L on 300 m² = **20 mm** in one go. Splitting into two applications gives **2 × 10 mm**.
  + Two smaller pulses reduce surface ponding and runoff risk on soils with modest infiltration rates and improve uniform infiltration, especially after rainfall.
* **Nutrient timing and losses**
  + At 1 g/L and typical microalgae composition, 6,000 L delivers roughly **0.42–0.60 kg N** and **0.03–0.09 kg P** per month.
  + Splitting delivers **half those amounts per event**, smoothing soil solution concentrations, reducing leaching pulses, and better aligning with plant uptake.
* **Soil biology and oxygen demand**
  + Organic-rich broths can drive short-term microbial respiration and oxygen drawdown near the surface. Smaller, more frequent doses lessen transient hypoxia and are gentler on roots and microbes.
* **Operational practicality**
  + Two 3,000 L runs are easier to pump, meter, and distribute evenly on a small block; they also provide a backup window if weather interrupts one pass.
* **Efficacy window**
  + If you’re leveraging living cells/metabolites, more frequent exposure can maintain biostimulant effects as viability and labile compounds decay over time.

When to avoid splitting: if labour/time is the bottleneck, infiltration is excellent, and runoff risk is minimal, a single 20 mm pass may be acceptable.

# 4. Eutrophication Potential

## Fertiliser Nutrient Content Analysis

This table is a **fertiliser usage and nutrient input comparison** between **conventional farming** and a **regenerative farming** approach, showing how much nitrogen (N) and phosphorus (P) each method applies per month.

### 1️⃣ Structure of the Table

* **Technique** → Farming method (Conventional vs Regenerative).
* **Chemical** → The specific fertiliser product used.
* **Units** & **kg/unit** → How many units are applied and the weight of each unit.
* **Class** → Fertiliser grade (e.g., 15-15-15 means 15% N, 15% P₂O₅, and 15% K₂O).
* **Mass percentages** → Nutrient content:
  + **N** = Nitrogen percentage.
  + **P₂O₅** = Phosphate percentage.
  + **P** = Elemental phosphorus percentage (P₂O₅ × 0.4364).
* **Mass (kg)** → Total fertiliser mass applied.
* **N applied** & **P applied** → Actual kilograms of nitrogen and phosphorus added to the soil.

### 2️⃣ What the Numbers Mean

#### Conventional Farming

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Fertiliser** | **Units × kg/unit** | **N%** | **P%** | **Total Mass (kg)** | **N Applied (kg)** | **P Applied (kg)** |
| DEEBAJ SUPERGRO NPK 15-15-15 | 2 × 25 kg | 15% | 6.55% | 50 | 7.50 | 3.27 |
| Agroharta 15-15-15 | 1 × 2 kg | 15% | 6.55% | 2 | 0.30 | 0.13 |
| Guang Fong 5-5-5 | 5 × 25 kg | 5% | 2.18% | 125 | 6.25 | 2.73 |
| Foliar fertiliser 10-5-12 | 1 × 1.5 kg | 10% | 2.18% | 1.5 | 0.15 | 0.03 |

**Total for Conventional**:

* **Mass applied**: 178.5 kg/month
* **Nitrogen applied**: **14.20 kg/month**
* **Phosphorus applied**: **6.16 kg/month**

#### Regenerative Farming

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Fertiliser** | **Units × kg/unit** | **N%** | **P%** | **Total Mass (kg)** | **N Applied (kg)** | **P Applied (kg)** |
| Microalgae water | 6000 × 0.001 kg | 5% | 0.5% | 6 | 0.30 | 0.03 |

**Total for Regenerative**:

* **Mass applied**: 6 kg/month
* **Nitrogen applied**: **0.30 kg/month**
* **Phosphorus applied**: **0.03 kg/month**

### 3️⃣ Key Insights

* **Nutrient load difference**: Conventional farming applies **~47× more nitrogen** and **~205× more phosphorus** than the regenerative method.
* **Fertiliser type**: Conventional uses multiple synthetic NPK blends and foliar feeds; regenerative uses a single biological input (microalgae water).
* **Environmental impact**: Lower nutrient application in regenerative farming reduces the risk of nutrient leaching, runoff, and water pollution.
* **Soil biology**: Regenerative inputs focus on feeding soil microbes and improving long-term fertility rather than delivering large, immediate nutrient doses.

### 4️⃣ Why This Matters

This table is essentially a **nutrient budget** — it tells you:

* How much fertiliser is being applied.
* The nutrient composition of each fertiliser.
* The actual nutrient load entering the soil each month.
* How different farming systems can drastically change nutrient inputs and potential environmental footprint.

## Nitrogen Contribution to Carbon Footprint

This table compares the **environmental impact of** **conventional** and **regenerative** farming systems, focusing on **nitrogen use**, **nitrate emissions**, **eutrophication potential**, and **carbon footprint**.

## **1️⃣ What Each Row Means**

|  |  |  |
| --- | --- | --- |
| **Metric** | **Meaning** | **Why It Matters** |
| **N used/year** | Total nitrogen applied annually (kg). | High nitrogen use can lead to nutrient leaching, water pollution, and greenhouse gas emissions. |
| **EF** (Emission Factor) | Amount of nitrate (NO₃⁻) emitted per kg of nitrogen applied. | Shows how efficiently nitrogen is retained vs lost to the environment. |
| **Emission** | Total nitrate emissions (kg NO₃⁻) per year. | Nitrate leaching contributes to groundwater contamination and eutrophication of rivers/lakes. |
| **Midpoint CF** | Conversion factor to express nitrate emissions in terms of nitrogen equivalents (kg N eq/kg NO₃⁻ emitted). | Used in life cycle assessment (LCA) to standardise nutrient pollution impacts. |
| **EP** (Eutrophication Potential) | Total nitrogen equivalents contributing to water pollution. | High EP means a greater risk of algal blooms, oxygen depletion, and aquatic ecosystem damage. |
| **Carbon EF** | Carbon emission factor — kg CO₂ equivalent per kg nitrogen applied. | Links fertiliser use to the climate change impact. |
| **C footprint** | Total carbon footprint from nitrogen use (kg CO₂ eq/year). | Shows contribution to greenhouse gas emissions from fertiliser production and application. |

## **2️⃣ What the Numbers Show**

### **Nitrogen Use**

* **Conventional**: 170.4 kg N/year
* **Regenerative**: 3.6 kg N/year
* **Reduction**: ~98% less nitrogen applied in regenerative farming.

### **Nitrate Emissions**

* EF is the same (1.33 kg NO₃⁻ per kg N applied) — meaning both systems lose nitrogen at the same proportional rate.
* But because regenerative farming applies far less nitrogen, total emissions drop from **226.6 kg NO₃⁻** to **4.8 kg NO₃⁻**.

### **Eutrophication Potential (EP)**

* Using the midpoint conversion factor (0.158), EP drops from **35.8 kg N eq** to **0.8 kg N eq** — a **97.9% reduction** in nutrient pollution risk.

### **Carbon Footprint**

* Carbon EF: 3.6625 kg CO₂ eq per kg N applied.
* Conventional nitrogen use results in **624.1 kg CO₂ eq/year**.
* Regenerative’s footprint is so small it’s almost negligible in this table.

## **3️⃣ Key Takeaways**

* **Massive nutrient load reduction**: Regenerative farming slashes nitrogen use by ~98%, which directly cuts nitrate emissions and eutrophication risk.
* **Water quality benefits**: Lower nitrate leaching means cleaner groundwater and reduced risk of harmful algal blooms.
* **Climate benefits**: Huge drop in CO₂ emissions from fertiliser production and application.
* **Same efficiency factor**: The emission factor (EF) is unchanged — the improvement comes from using far less nitrogen, not from changing nitrogen loss rates.

## Phosphorus Contribution to Carbon Footprint

This table compares conventional vs regenerative systems for phosphorus use and its environmental impacts: how much P is applied, how much is emitted, how that translates to eutrophication potential, and the carbon footprint associated with P inputs.

### **What each row means**

|  |  |  |
| --- | --- | --- |
| **Metric** | **Meaning** | **Why it matters** |
| P used/year | Annual elemental phosphorus applied (kg P). | High inputs raise loss risk and downstream water impacts. |
| Emission factor | Proportion of applied P that is lost to the environment as P. | Converts application into expected emissions. |
| Emission | Annual phosphorus emitted (kg P). | Direct driver of freshwater eutrophication. |
| Midpoint CF | Characterisation factor to convert emitted P to phosphate equivalents (kg PO4 eq per kg P). | Standardises impacts for Life Cycle Assessment. |
| EP | Eutrophication potential (kg PO4 eq). | Higher EP means higher risk of algal blooms/oxygen depletion. |
| Carbon EF | kg CO2e per kg P applied. | Captures production and supply-chain emissions of P fertiliser. |
| C footprint | Annual CO2e from P inputs. | Indicates climate impact of phosphorus fertilisation. |

### **What the numbers show**

* **P use**
  + Conventional: 74.0 kg P/year.
  + Regenerative: 0.4 kg P/year.
  + **Reduction:** ~99.5%.
* **Phosphorus emissions**
  + Emission factor: 0.05 kg P emitted per kg P applied (same for both).
  + Conventional emission: 3.7 kg P/year.
  + Regenerative emission: ~0.02 kg P/year (shown as 0.0 due to rounding).
  + **Reduction:** ~99.5%.
* **Eutrophication potential**
  + Midpoint CF: 0.100 kg PO4 eq per kg P emitted.
  + Conventional EP: 0.370 kg PO4 eq.
  + Regenerative EP: 0.002 kg PO4 eq.
  + **Reduction:** 99.5%.
* **Carbon footprint from P inputs**
  + Carbon EF: 3.125 kg CO2e per kg P applied.
  + Conventional: 231.3 kg CO2e/year.
  + Regenerative: ~1.25 kg CO2e/year.
  + **Reduction:** ~99.5%.

### **Key takeaways**

* **Massive load reduction:** Regenerative management slashes P inputs, emissions, eutrophication potential, and carbon footprint by roughly the same ~99.5% because the emission and characterisation factors are identical across systems, so impact scales with the amount applied.
* **Water quality win:** Cutting emitted P from ~3.7 to ~0.02 kg/year drives the EP drop from 0.370 to 0.002 kg PO4 eq.
* **Climate benefit:** Lower P inputs also cut embedded CO2e from ~231 to ~1.25 kg/year.
* **Mechanism:** Improvements arise from dramatically lower P application rather than a change in emission efficiency.

## Carbon Footprint Sources

### 1️⃣ ScienceDirect study (Balasuriya et al., 2022 – Science of the Total Environment)

This paper assessed **freshwater and marine eutrophication potential** from fertiliser use in Thailand using a **Life Cycle Assessment (LCA)** framework (ISO 14040).  
 Key points that validate your factors:

* **Emission Factors (EFs)**: The study quantified nitrogen and phosphorus losses from fertiliser application using **widely applied emission inventory models**. These models are standard in LCA when direct field data is unavailable.
* **Characterisation Factors (CFs)**: The nutrient losses were converted into eutrophication potential using **Thai‑specific CFs** derived from recognised LCIA methods (e.g., ReCiPe 2016, IMPACT World+).
* The authors explicitly note that CFs are based on **fate and effect modelling** — i.e., how much of an emitted nutrient actually reaches and impacts aquatic ecosystems — and that these vary by location.
* They stress that nitrate (NO₃⁻) is the **dominant driver** of marine eutrophication potential (92.7% of impact), which aligns with your use of nitrate‑based EF in the table.

**Why this matters:** Your EF of **1.33 kg NO₃⁻ per kg N applied** and CF of **0.158 kg N eq/kg NO₃⁻ emitted** are consistent with the type of spatially‑differentiated, peer‑reviewed factors used in this study.

### 2️⃣ WIT Press study (Havukainen, 2018 – Int. J. Sustainable Development and Planning)

This paper focuses on **carbon footprint evaluation of biofertilisers** using LCA.  
 Key points that validate your carbon EF:

* The study calculated **carbon footprints for nitrogen in mineral fertilisers** ranging from **1.9–7.8 kg CO₂ eq per kg N**.
* Your carbon EF of **3.6625 kg CO₂ eq/kg N applied** falls well within this published range.
* The methodology follows **ISO 14040** and the **GHG Protocol**, allocating emissions from production processes to nutrient content — exactly the approach you’ve used.

**Why this matters:** Your carbon EF is not an invented figure — it’s in line with peer‑reviewed LCA results for fertiliser production emissions.

## Calculation of Carbon Footprint by Microalgae Water

### **Verification of carbon uptake and footprint**

#### **Assumptions and definitions**

* **C uptake factor meaning**:  
   [ \text{C uptake factor}=\text{C mass fraction in dry biomass}\times \frac{44}{12}\ \left(\frac{\mathrm{kg\ CO\_2}}{\mathrm{kg\ C}}\right) ]
* **Given values**:
  + **C uptake by microalgae**: (-1.83\ \mathrm{kg\ CO\_2eq/kg\ dry})
  + **Calculated footprint**: (-131.76\ \mathrm{kg\ CO\_2eq})

#### **Math check**

* **Is −1.83 kg CO2/kg DW plausible?** If microalgae dry matter contains ~50% carbon: [ 0.50 \times \frac{44}{12}=1.833\ \mathrm{kg\ CO\_2/kg\ dry} ] This matches the provided factor (sign negative for uptake).
* **Does the footprint match a mass of biomass?** [ \text{Footprint} = \left(-1.83\ \frac{\mathrm{kg\ CO\_2eq}}{\mathrm{kg}}\right)\times m\_{\text{dry}} ] Solving for (m\_{\text{dry}}): [ m\_{\text{dry}}=\frac{131.76}{1.83}=72.0\ \mathrm{kg} ] So (-131.76\ \mathrm{kg\ CO\_2eq}) corresponds exactly to 72 kg dry microalgae.

#### **Consistency with the 1 g/L “microalgae water” assumption**

* **Implied application volume**:  
   At (1\ \mathrm{g/L}) (i.e., (0.001\ \mathrm{kg/L})), delivering (72\ \mathrm{kg}) dry requires: [ \frac{72\ \mathrm{kg}}{0.001\ \mathrm{kg/L}}=72{,}000\ \mathrm{L} ] That volume is consistent with your calculated footprint if the 1 g/L concentration is used.

#### **Sensitivity and caveats**

* **Carbon fraction variability**: If (x\_C=0.45)–(0.55), uptake factor ranges [ 0.45\times \frac{44}{12}=1.65\ \text{to}\ 0.55\times \frac{44}{12}=2.02\ \mathrm{kg\ CO\_2/kg\ dry} ] For 72 kg dry, the footprint would be (-118.8) to (-145.4\ \mathrm{kg\ CO\_2eq}).
* **Permanence and system boundary**: The −1.83 kg CO2/kg DW reflects biogenic uptake in biomass. If the biomass decomposes or is respired, much of that CO2 returns to the atmosphere; cultivation and processing energy/emissions can further offset the credit. Your net LCA result depends on fate of biomass and included processes.

#### **Verdict**

* **The numbers are internally consistent and physically reasonable**: −1.83 kg CO2eq/kg dry (≈50% C) and −131.76 kg CO2eq total for 72 kg dry at 1 g/L concentration. If you provide the actual carbon content and applied volume, I can refine the uptake and uncertainty band.

“Recent research indicates that one kilogram of algae can capture around 1.83 kg of CO₂. Moreover, some algal species are capable of using various carbon oxides (COx) — including carbon monoxide (CO), carbon dioxide (CO₂) — as well as nitrogen oxides (NOx), such as nitric oxide (NO) and nitrogen dioxide (NO₂), as nutrient sources alongside CO₂ (Joint Research Centre, 2023; Speight, 2019).” <https://doi.org/10.1016/j.jclepro.2024.144576>

# 5. More Actionable Insights

## **1️⃣ Maximise Yields While Minimising Environmental Impact**

### **Soil Nutrition & Input Strategy**

* **Calibrate microalgae applications**:  
   Maintain ~6 g DW/m²/month but **split into 2–3 doses** to reduce nutrient surges, improve plant uptake, and avoid runoff — especially in wet months.
* **Bridge nutrient gaps** in early regenerative years:  
   Integrate small, **targeted organic amendments** (e.g., compost, poultry manure) pre‑flower to ensure nutrient sufficiency in critical growth stages.
* **Varietal/crop specificity**:  
   Use slightly different nutrient timing for Limau Nipis vs Limau Kasturi — Nipis appears more sensitive to nutrient fluctuations.

### **Integrated Pest/Disease Management**

* Shift to **preventive controls**: encourage beneficial insects, companion planting, and early scouting.
* Use **low‑residue bio‑pesticides** strategically at pest threshold triggers, not as a calendar spray.
* Increase **canopy airflow** by pruning after each major flush to reduce fungal risk.

## **2️⃣ Minimise Chemical Inputs & Reduce Soil/Water Contamination**

### **Fertiliser**

* Eliminate high‑frequency synthetic NPK from regenerative plots; reserve for exceptional yield‑threat conditions confirmed by leaf/soil test.
* Match N & P application rates to **crop removal + soil status**, avoiding habitual over‑application.

### **Pesticide**

* Consolidate sprays by **rotating actives** with bio‑controls, reducing chemical persistence and resistance build‑up.
* Use **buffer strips** and **mulch bands** to slow runoff from treated rows.

### **Water/Nutrient Management**

* Convert large single fertigation events into **multi‑pulse irrigation** — promotes nutrient retention in root zone and lowers loss to leaching.
* In monsoon months, reduce fertiliser rate by 20–30% to align with reduced uptake and higher leaching risk.

## **3️⃣ Tracking Progress Toward Long‑Term Soil Health Restoration**

You already have strong baseline data (SOM, SOC, CEC, TC, TN, SQI), so build a **repeatable monitoring framework**:

|  |  |  |  |
| --- | --- | --- | --- |
| **Metric** | **Baseline Frequency** | **Target (3–5 yrs)** | **Notes** |
| SOM % | Every 6 months | +2–3 pts | Indicator of organic matter build‑up |
| CEC (meq/100g) | Annual | >40 | Links directly to nutrient retention |
| TN & TC % | Every 6 months | TN >0.4%, TC >8% | Shows N cycling and C sequestration |
| SOC/SOM ratio | Annual | ~58% | Stability of organic matter |
| LGPP (%) | Monthly | Reduce toward pre‑regen levels | Especially for Limau Nipis |
| EP (kg N/P eq) | Annual LCA calc | Maintain ≥90% reduction vs conventional | Confirms water quality benefit |
| Carbon footprint | Annual LCA calc | Net negative CO₂e | Supports carbon claims |

**Operational note:** Use the same sampling locations and lab for consistency. Keep both raw data and interpreted scores (e.g., SQI) for time‑series trends.

## **4️⃣ Specific Interventions for the Low‑Grade Product Issue**

* **Limau Nipis**: Tighten nutrient release timing, introduce short‑term pest buffer sprays at fruit‑set, and reduce canopy moisture load in wet season.
* Maintain **harvest uniformity**: pick fruit at consistent maturity to avoid size/colour downgrades.
* Include **post‑harvest grading review** — train graders to separate cosmetic from structural defects; some “B” fruit may be saleable into niche or processing markets.

## **5️⃣ Phased Implementation Plan**

|  |  |  |  |
| --- | --- | --- | --- |
| **Phase** | **Duration** | **Key Actions** | **KPI Focus** |
| **Stabilisation** | 0–6 mo | Split microalgae apps, targeted organic boosts, pest scouting | Yield, LGPP, N & P input cuts |
| **Optimisation** | 6–18 mo | Adjust timing per crop, expand IPM, reduce chemical sprays to <25% of conventional | EP reduction, CEC gains |
| **Expansion** | 18+ mo | Scale regenerative practices to other sites, refine carbon & nutrient credits for revenue streams | SQI improvement, CO₂e balance |

## **6️⃣ Big‑Picture Benefit Framing**

* **Yield**: Your data shows volume jumps of 60–86% post‑transition — protect that gain with nutrient timing and pest vigilance.
* **Environment**: Maintain >97% reduction in EP and ~99% cut in N/P use relative to conventional baseline.
* **Carbon**: Microalgae uptake gives ~−132 kg CO₂e per 72 kg DW — small now, but scale‑responsive.
* **Economics**: Even with higher LGPP in Nipis, revenue/fertiliser cost margins improved. Bridging the quality dip can compound profitability.

#### **5.1. Soil and Nutrient Management: Beyond Fertilisers**

##### **5.1.1. Soil Analysis and Acidity Correction**

A crucial first step in any regenerative transition is a thorough understanding of the existing soil conditions. In Malaysia, soils are often acidic, which can lead to deficiencies in essential microelements.6 For citrus, an optimal soil pH range is between 6.0 and 7.0.16 To establish a baseline and guide the correction process, it is recommended to conduct a comprehensive soil analysis at multiple depths, including 0–15 cm, 15–30 cm, and 60 cm.16

Based on the test results, liming materials such as calcitic or dolomitic limestone can be used to raise the soil pH to the desired range.16 Dolomitic lime is particularly beneficial as it also supplies calcium and magnesium, two essential plant nutrients.17 For new plantings, the lime should be applied 6-8 weeks prior to planting and worked into the soil as deeply as possible.16 In established orchards, a surface application is suitable, especially in the absence of heavy rains.16 The rate of application should always be guided by the results of the soil test to ensure effective pH correction without over-liming.16

##### **5.1.2. The Central Role of Composting**

Composting is not merely a method of waste disposal in a regenerative system; it is a central pillar of soil fertility management. Compost adds vital organic matter and nutrients to the soil, significantly improving its water and nutrient-holding capacity and enhancing soil structure.18 This rich organic material also stimulates a diverse community of beneficial microorganisms, which play a critical role in nutrient cycling, disease suppression, and overall soil health.7

The creation of compost should incorporate local, on-farm biomass, which is a key component of building a "closed-loop system".5 This process transforms a conventional problem—the disposal of crop residue and organic waste—into a regenerative solution.14 Conventional farming often views this material as a problem to be discarded, sometimes through burning, which releases carbon into the atmosphere and depletes the land.20 Regenerative agriculture, by contrast, treats this biomass as a valuable resource to be recycled directly back into the farm ecosystem.1 This fundamental shift in perspective also translates into significant economic benefits. By utilizing on-farm resources, the farm reduces its reliance on expensive, external synthetic fertilizers, thereby lowering input costs and debt for smallholder farmers.3

For application, compost should be applied to the soil surface, where it acts as a mulch.18 This method reduces the risk of nitrogen loss through volatilization and avoids interference with mechanical harvesting.18 A suitable annual application rate is typically 1 to 5 tons per acre, with the exact amount determined by soil analysis and the specific needs of the orchard.18

#### **5.2. Ground Cover and Intercropping: A Living Mulch System**

##### **5.2.1. The Strategic Use of Cover Crops**

Cover crops are a cornerstone of regenerative citrus farming, serving as a living mulch system that protects and enriches the soil year-round.1 They are critical for preventing erosion from heavy rains, suppressing weeds, and contributing to soil fertility.1 A particularly promising cover crop for citrus cultivation in the humid tropics is *Mucuna bracteata*, a species of leguminous plant from the Fabaceae family.23 This cover crop is a rapid grower, with a reported growth rate of 10–15 cm per day in warm, humid conditions with consistent rainfall.23 It is a highly effective nitrogen-fixer, providing a natural source of nitrogen to the soil via its leguminous nodules, which can significantly improve soil fertility and health.23 Additionally, its dense foliage creates a shade canopy that effectively smothers and controls weed populations, reducing the need for herbicides.23 The success of *M. bracteata* in Malaysian oil palm and rubber plantations provides a compelling, location-specific precedent for its use in citrus orchards.23

##### **5.2.2. Intercropping for Biodiversity and Yield**

Increasing plant diversity through intercropping is a key regenerative practice that builds a more resilient and productive ecosystem.1 Instead of a single crop, the practice involves growing other beneficial crops alongside the primary citrus trees. Research has shown that intercropping can lead to superior outcomes compared to monoculture. For example, studies have demonstrated that citrus orchards intercropped with legumes, such as soybean and chickpea, produced significantly higher fruit yields than orchards without intercrops.26 The legume intercrops enrich the soil by biologically fixing nitrogen and improving nutrient availability, leading to higher levels of essential nutrients in the leaves of the citrus trees.26

#### **5.3. Integrated Pest and Disease Management (IPM): A Biological Approach**

##### **5.3.1. Local Pest and Disease Profile**

Citrus cultivation in Malaysia's humid climate faces significant challenges from a range of pests and diseases.6 The most critical threats include:

* **Asian Citrus Psyllid (*Diaphorina citri*):** This pest is the primary vector for Citrus Greening disease (Huanglongbing or HLB), for which there is no known cure.27
* **Citrus Canker (*Xanthomonas axonopodis* pv *citri*):** A bacterial disease that causes damaging lesions on leaves, stems, and fruit.28
* **Gummosis (*Phytophthora nicotianae*):** A soil-borne fungus that infects the trunk and roots, leading to dieback and decline.28
* **Citrus Scab (*Elsinoe fawcetti*):** A fungal disease that is particularly problematic for *limau kasturi*, causing scabby lesions on fruit and leaves.28

The perennial humidity and rainfall create ideal conditions for these pathogens to thrive and spread.6

##### **5.3.2. A Regenerative IPM Strategy**

A regenerative approach to pest and disease management stands in stark contrast to conventional, chemical-intensive methods. The research explicitly states that a heavy reliance on synthetic pesticides has been ineffective in preventing the spread of diseases like HLB in Asia and often leads to an unsustainable cycle of chemical dependency.27 This failure is rooted in a fundamental systemic flaw. The overuse of broad-spectrum pesticides indiscriminately kills both pests and their natural enemies, creating a biological vacuum.27 Pests, with their short life cycles, can then rebound rapidly without any natural predators to keep their populations in check, forcing farmers into an escalating cycle of chemical applications.

The regenerative IPM strategy offers a viable and more effective alternative by prioritizing the establishment of a resilient, biologically balanced ecosystem.7 The goal is not the complete elimination of pests but the suppression of their populations to levels where they no longer cause significant economic damage.31 This is achieved through a multi-pronged approach:

* **Prevention and Hygiene:** The most effective defense is a proactive one. This includes using pathogen-free planting material, regular monitoring for early signs of pests or disease, and the swift removal of any infected trees.27
* **Biological Control:** This involves encouraging and, if necessary, introducing natural enemies of pests. Specific examples include the use of predatory mites, such as *Amblydromalus limonicus*, to control thrips and whitefly, and parasitic wasps for the Asian Citrus Psyllid.27 These beneficial insects are key allies in maintaining a balanced ecosystem and preventing pest outbreaks.22
* **Organic and Cultural Controls:** A variety of organic substances and cultural practices can be employed. This includes applying botanical insecticides like neem oil and insecticidal soaps against soft-bodied insects, and using compost tea applications to boost plant health and resistance.22
* **Physical Barriers:** The use of physical barriers like windbreaks is a highly effective cultural practice for controlling diseases like Citrus Canker.34 Since Canker bacteria are often spread by windblown rain, windbreaks can reduce wind speed to below 20 mph, a critical threshold for infection, thereby limiting the spread of the disease.34

This regenerative approach to pest and disease management is a departure from the costly and ineffective chemical cycle. It restores the farm’s own biological defenses, reduces the need for expensive synthetic inputs, and fosters a more robust and self-sustaining agricultural system.1