

Nutrient recovery strategies for sustainable urban agriculture in soilless and open-field systems



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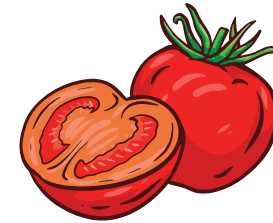
Main objective:

Determine the feasibility of applying recovered nutrients in both soilless and open-field systems, and assessing its impact on yield, quality traits and environmental impact

Chapter 1: Introduction

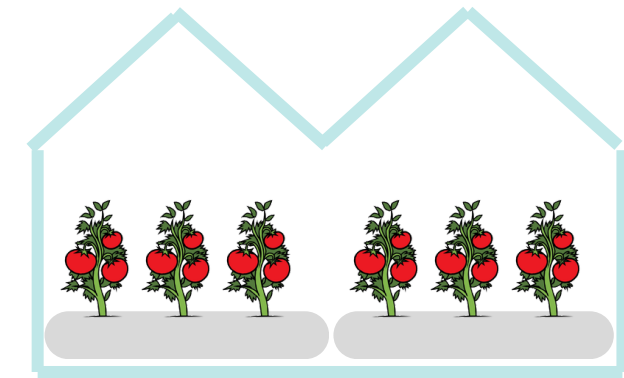
Chapter 2

Tomato



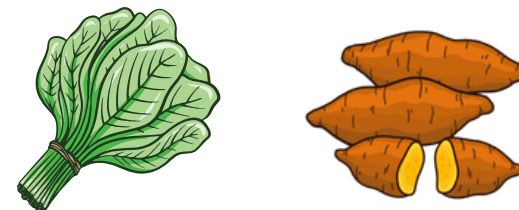
Chapter 3

Greenhouse



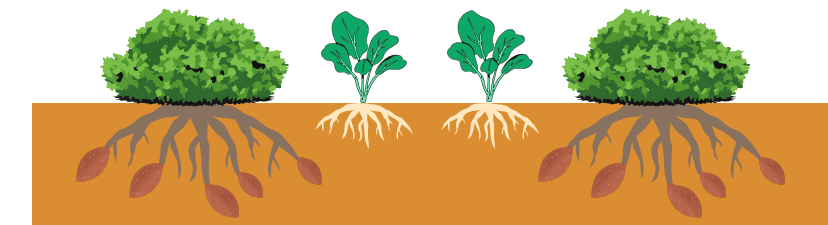
Chapter 4

Spinach and sweet
potato



Chapter 5

Open-field



Chapter 6: General discussion

Chapter 7: Conclusions

Chapter 1: Introduction



The challenges of the food system

- World population will reach 10 billion people by 2050
- An increase of 70 - 100% in food production is needed
- Agriculture is responsible of 21 - 37% of global anthropogenic GHGs emissions
- Agriculture occupies 44% of the world's habitable land

The need to reduce miner fertilizers

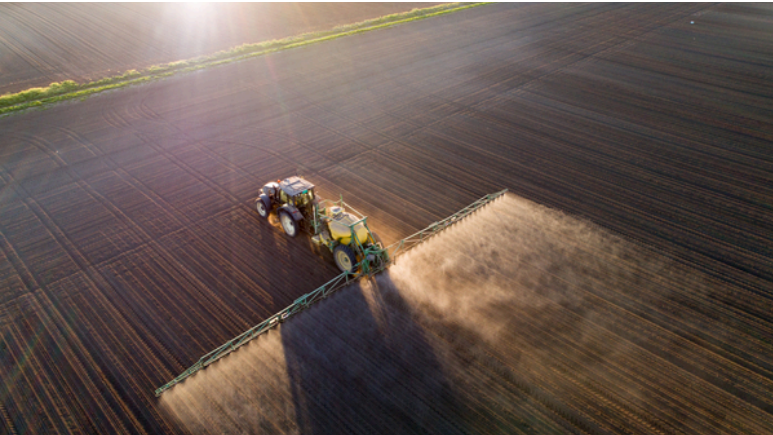
Energy consumption



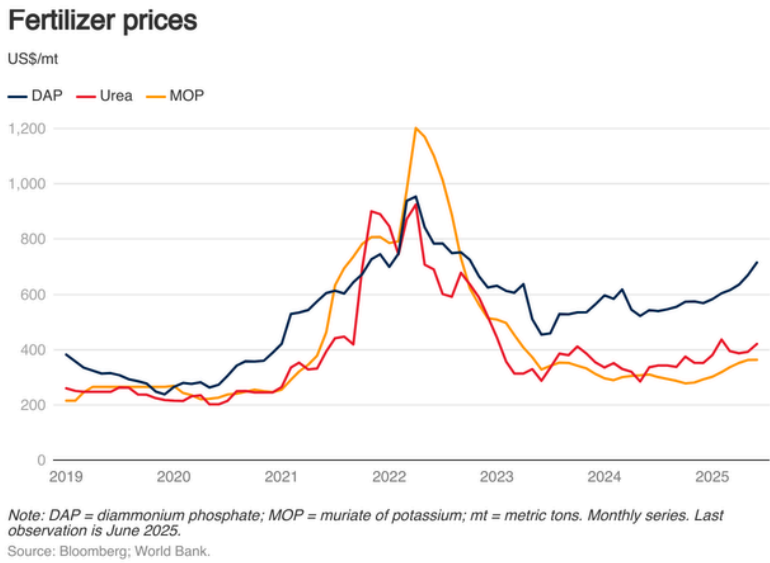
Consumption of finite resources



GHGs emissions



Prices fluctuations



Geopolitical conflicts



Urban agriculture (UA)



Transportation



Storage



Food loss



Enhances
biodiversity



Improves air
quality



Reduces heat
island effect



Recovered nutrients implementation

Struvite (NH_4MgPO_4)



Compost



Ramial chipped wood (RCW)



Evaluating the effectiveness of recovered nutrients

- Potential nutrient limitations
- Logistical constraints
- Risk of nutrient imbalances and toxicity
- Possible impacts on yield, marketability and environmental impact

Case studies





Methods

Data collection



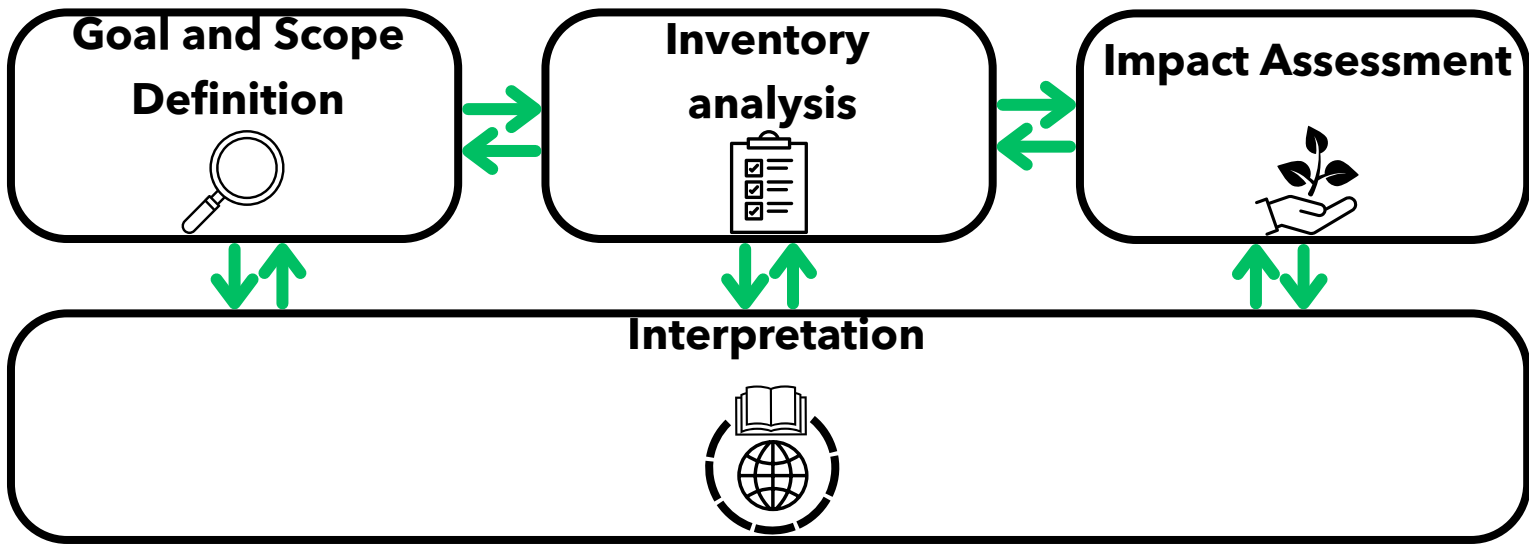
Measurements of direct emissions



Quality analysis



Life Cycle Assessment (LCA)



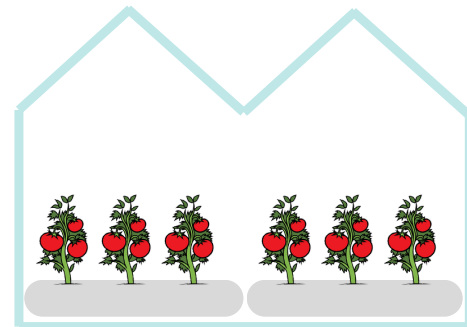
Statistical analysis

```
1 # Load required libraries
2 library(readxl)
3 library(tidy)
4 library(dplyr)
5 library(multcomp)
6 library(multcompview)
7 library(openxlsx) # For writing Excel file
8
9 # === 1. Load the Excel data ===
10 data_wide <- read_excel("C:/users/1655821/OneDrive - UAB/Documents/PhD/Article
11                        sheet = "g_plant_day")
12
13 # === 2. Convert from wide to long format ===
14 data_long <- pivot_longer(data_wide,
15                           cols = everything(),
16                           names_to = "Experiment",
17                           values_to = "Yield")
18
19 # === 3. Clean data ===
20 data_long <- na.omit(data_long)
21
22 # === 4. Fix names and levels ===
23 data_long$Experiment <- gsub("-", "", data_long$Experiment)
24 data_long$Experiment <- factor(data_long$Experiment)
25
26 # === 5. ANOVA and Tukey HSD ===
27 anova_model <- aov(Yield ~ Experiment, data = data_long)
28 tukey_glht <- glht(anova_model, linfct = mcp(Experiment = "Tukey"))
29 tukey_letters <- cld(tukey_glht)
30
31 # === 6. Summarize data (mean, SD) ===
32 summary_table <- data_long %>%
33   group_by(Experiment) %>%
34   summarise(
35     mean_yield = mean(Yield),
36     sd_yield = sd(Yield),
37     .groups = "drop"
38   )
```


Chapter 1: Introduction

Chapter 2

Hydroponic tomato
in an i-RTG



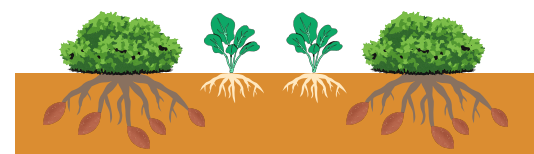
RQ1: What are the key agronomical, technical and environmental drivers of productivity and sustainability in long-term hydroponic tomato cultivation in an i-RTG?

RQ2: How does struvite fertilization influence quality traits and consumer preferences in hydroponic tomato production?

Chapter 3

Chapter 4

Open-field cultivation of
spinach and sweet potato in a
peri-urban field



RQ3: What are the production and environmental implications of applying recovered nutrients for soil-based spinach and sweet potato cultivation?

RQ4: How can RCW or other carbon-rich residues be promoted to regenerate degraded peri-urban soils and ensure sustainable crop production?

Chapter 5

Chapter 6: General discussion

Chapter 7: Conclusions

RQ5: Can recovered nutrients replace mineral fertilizers without compromising productivity, quality and sustainability for horticultural production in soilless and open-field systems?

Chapter 2: Sustainable resource optimization for tomato cultivation in a rooftop greenhouse: an 8-year case study



The i-RTG of the ICTA-UAB



- Area: 125 m²
- Hydroponic system with drip irrigation and perlite
- Covering material: polycarbonate

Research question and objective

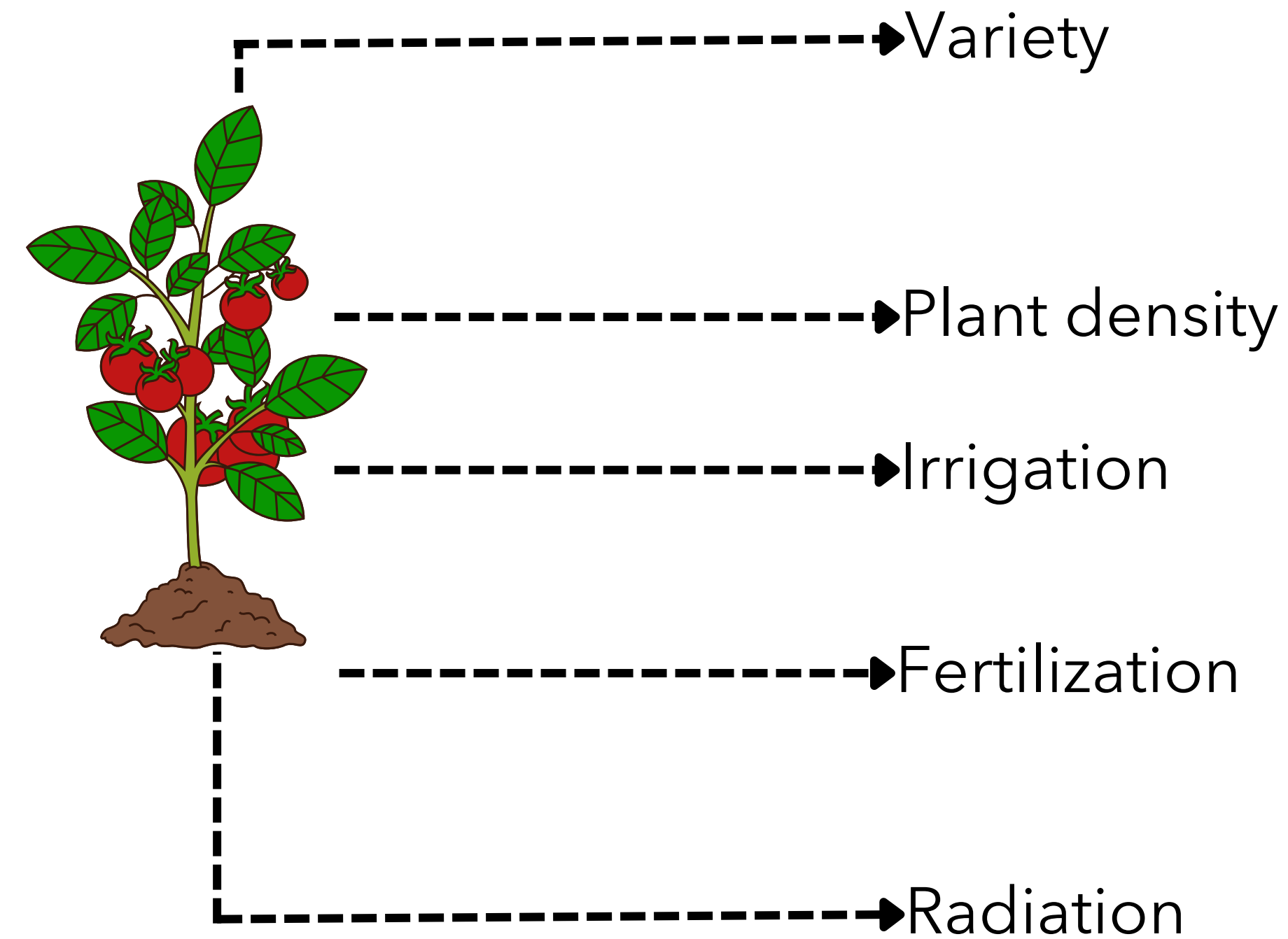
Research question n.1:

What are the key agronomical, technical and environmental drivers of productivity and sustainability in long-term hydroponic tomato cultivation in an i-RTG?

Research objective n.1:

Analysis of eleven crop cycles of hydroponic tomato from 2015 and 2023 in an i-RTG to identify long-term strategies for sustainable production.

Analysis of 11 crop cycles during 8 years



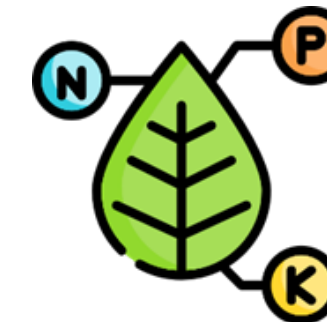
- Arawak
- Tomawak
- Gigawak
- Siranzo
- Rosa de Cadiz
- Montgrí
- 3 plants per bag of perlite: 2015-2021
- 2 plants per bag of perlite: 2022-2023



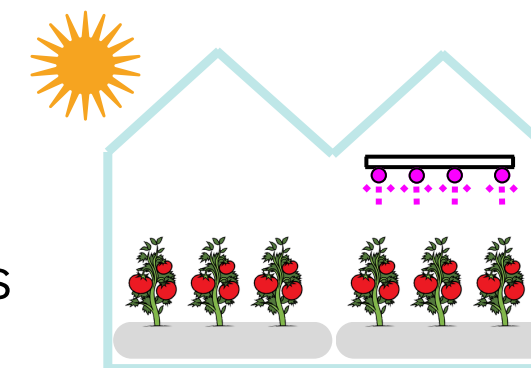
- Municipal water
- Rainwater



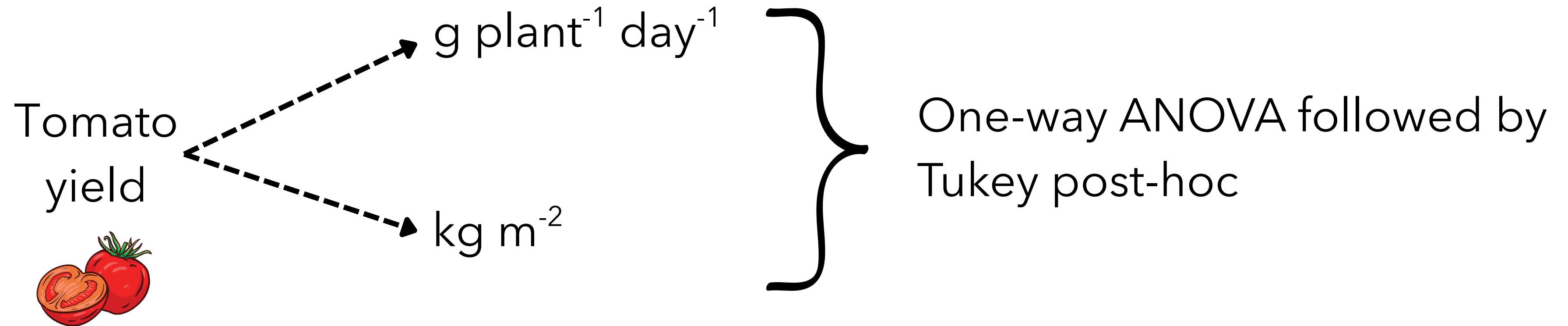
- Mineral fertilization
- Recirculation of nutrients
- Struvite



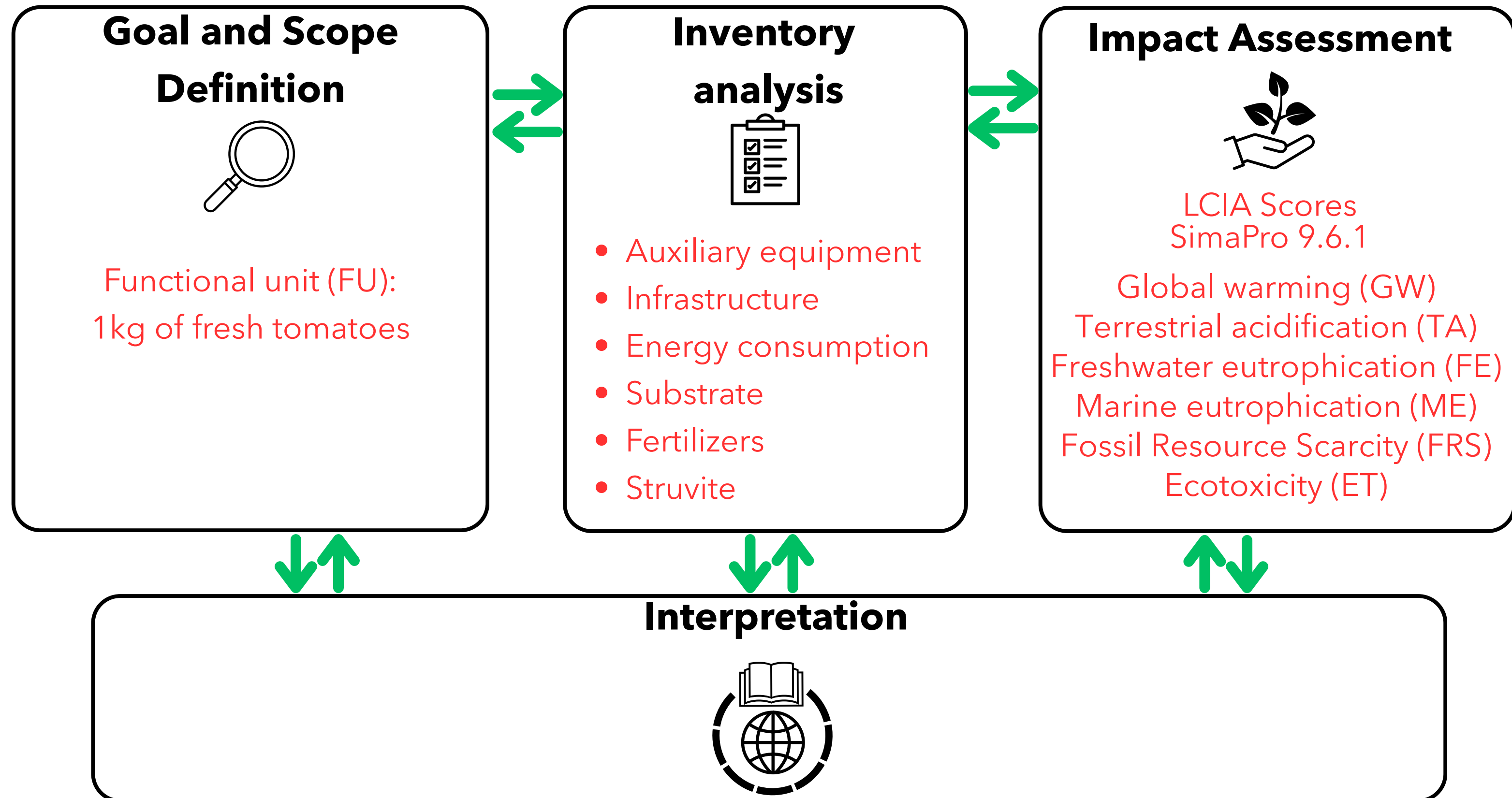
- Solar
- LED lights



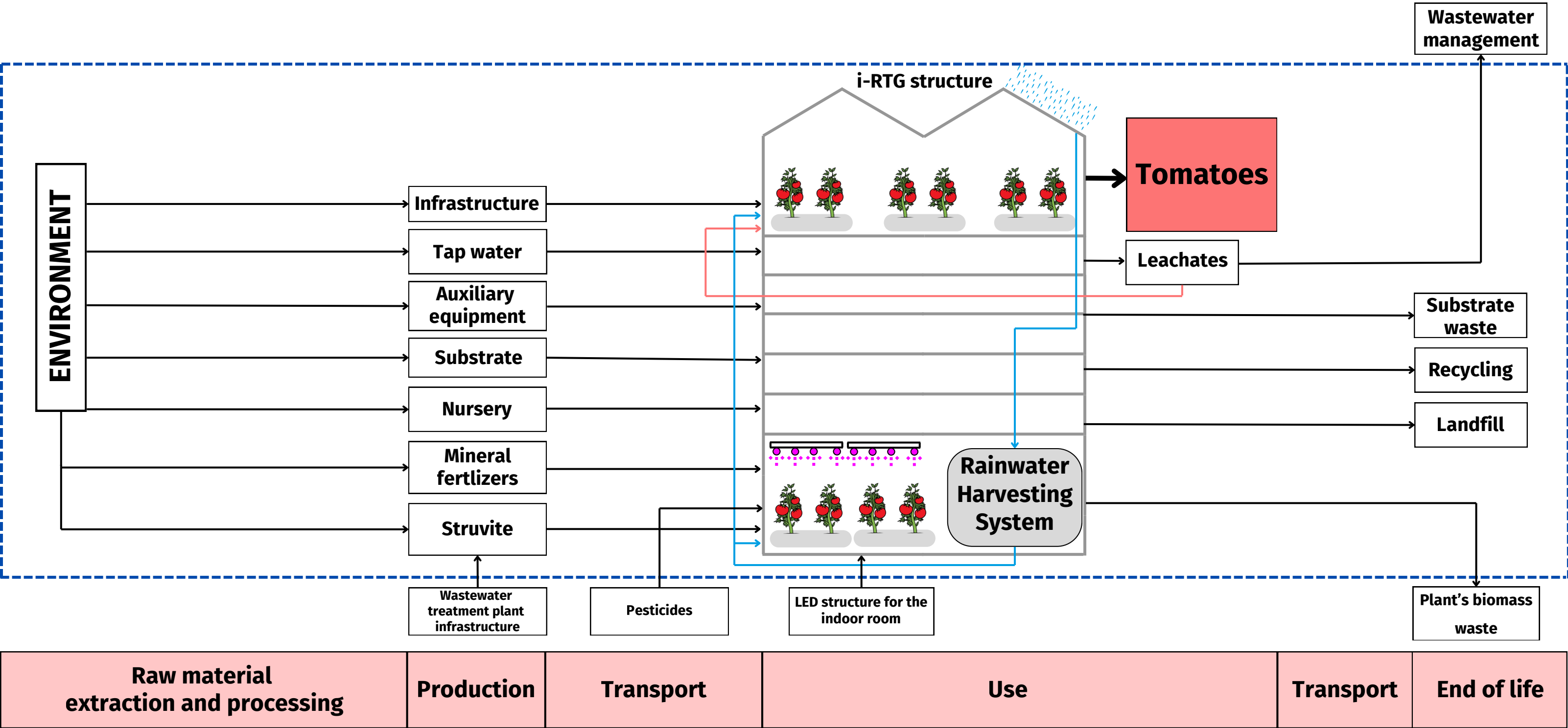
Yield normalisation



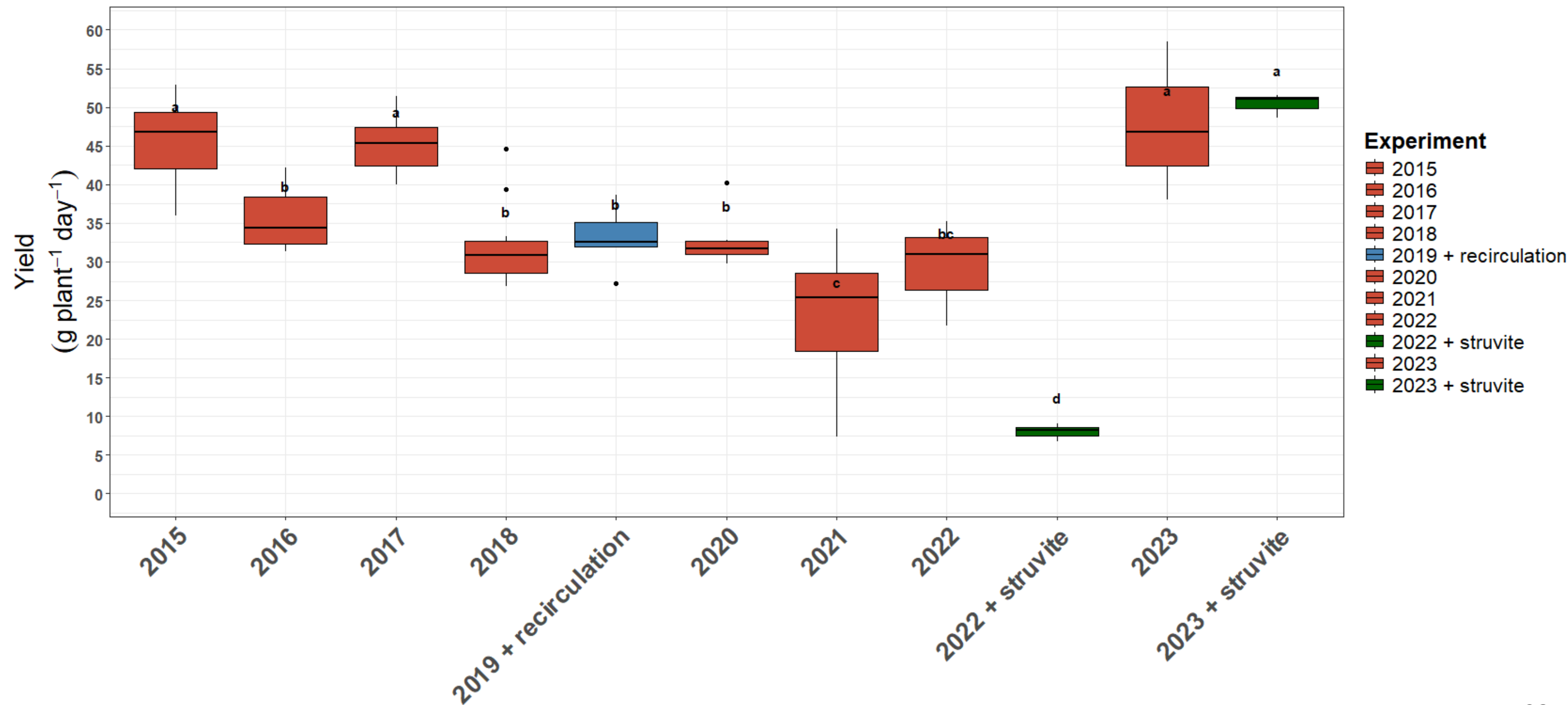
Life Cycle Assessment (LCA)



Life Cycle Assessment (LCA)

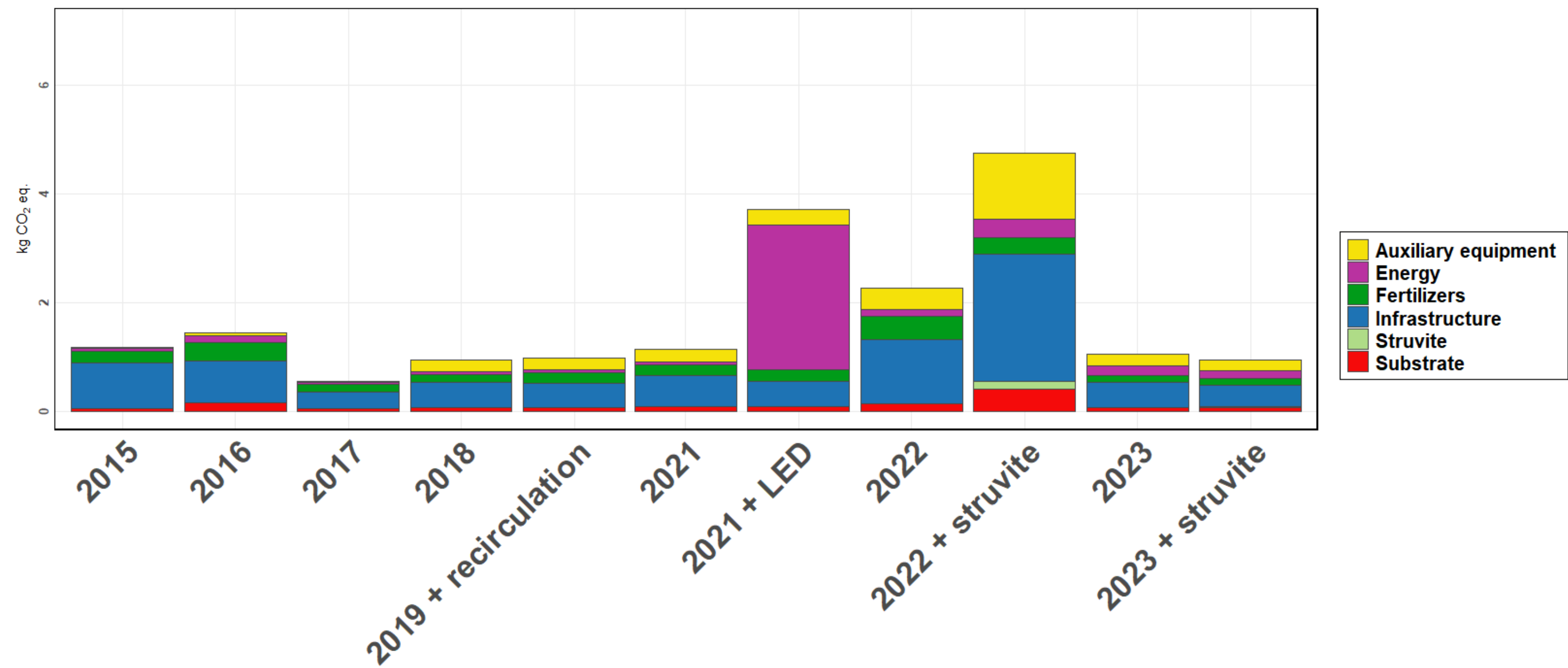


Results



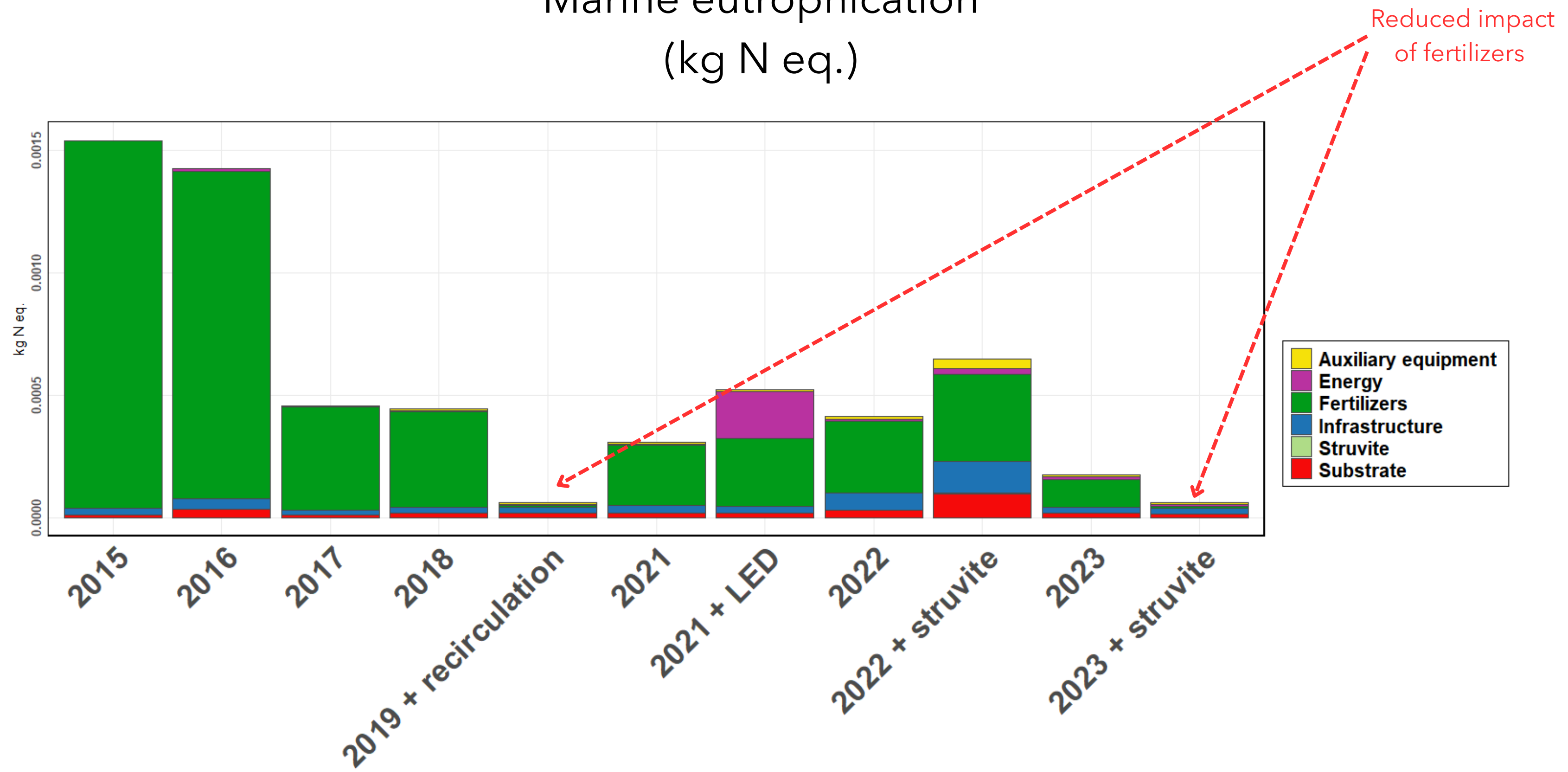
Results

Global warming
(kg CO₂ eq.)

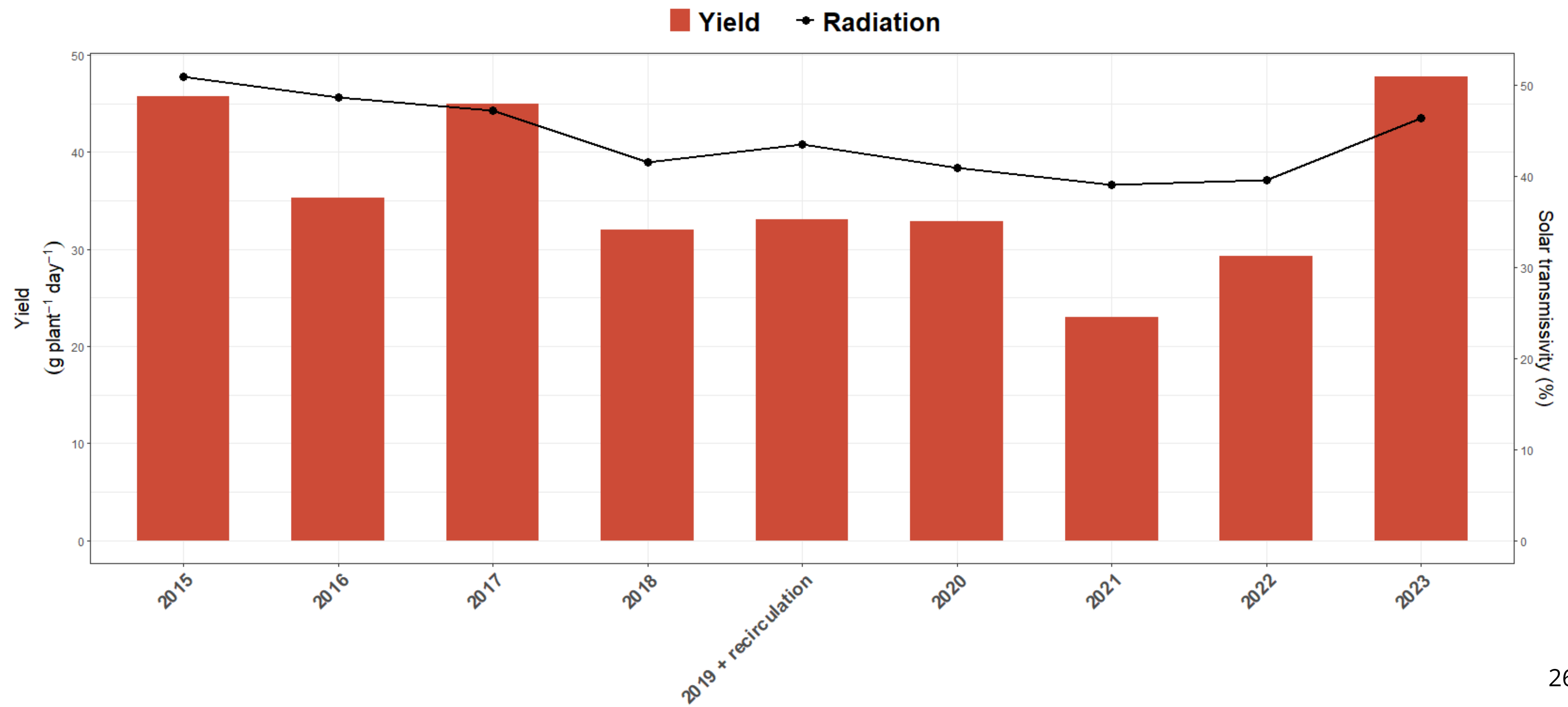


Results

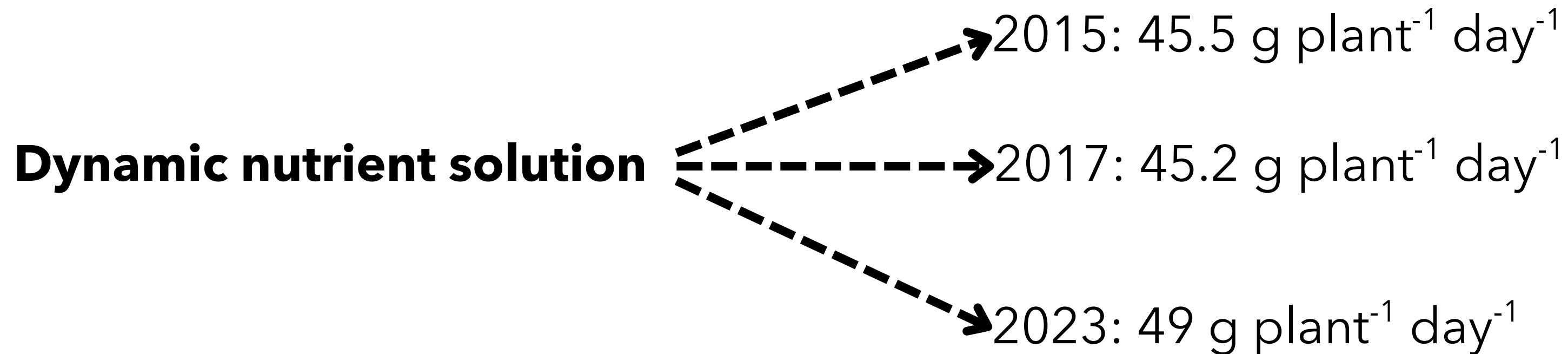
Marine eutrophication
(kg N eq.)



Key actors for successful yields: optimal solar radiation



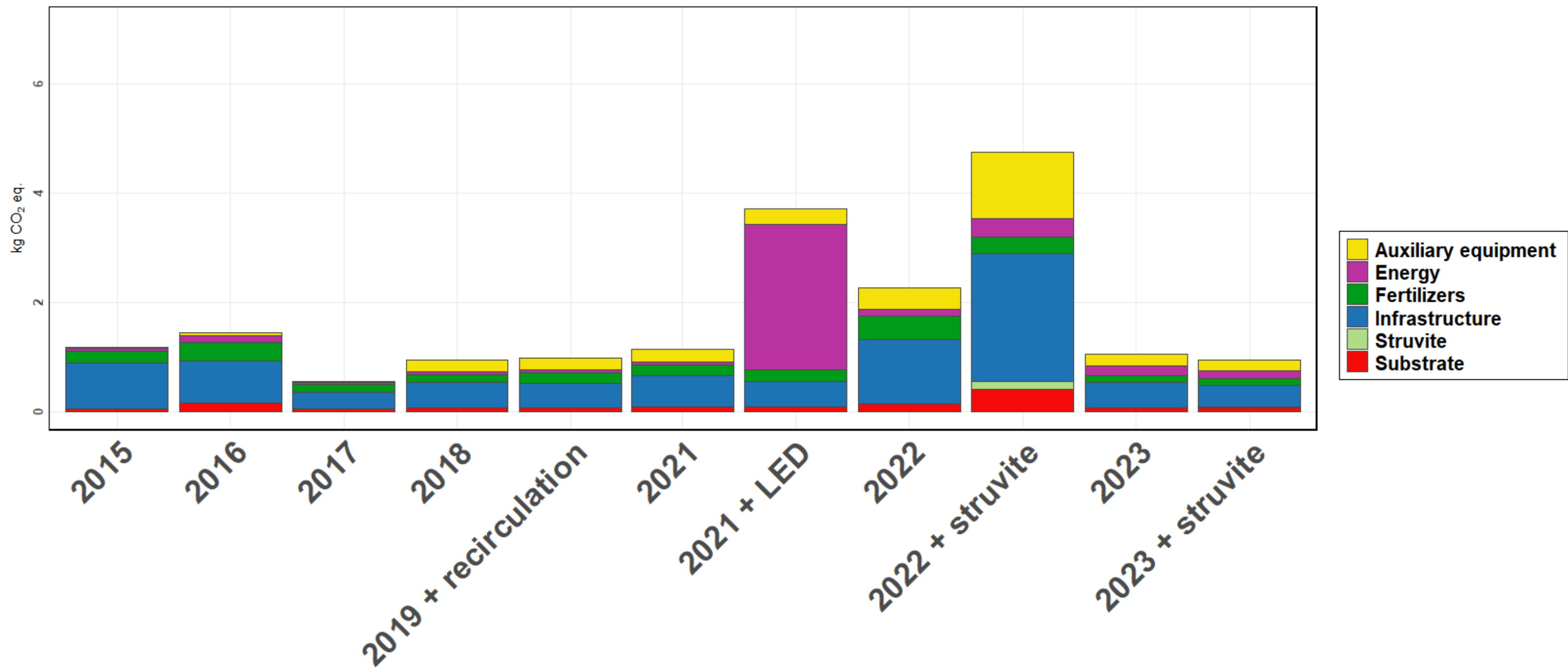
Key actors for successful yields: optimal nutrient management



Addition of NH₄⁺ -----> 2023: 49 g plant⁻¹ day⁻¹

Key drivers of LCIA: productivity (kg m⁻²), fertilization and energy use

Global warming
(kg CO₂ eq.)



Conclusions

- Struvite (100 g plant^{-1}) led to the highest yields ($49 \text{ g plant}^{-1} \text{ day}^{-1}$)
- Regularly substituting the covering materials is essential
- Environmental impacts are mainly driven by the productivity (kg m^{-2}), due to the impacts allocated to the greenhouse components
- ME is minimized in closed systems (2019) and with struvite (2023)

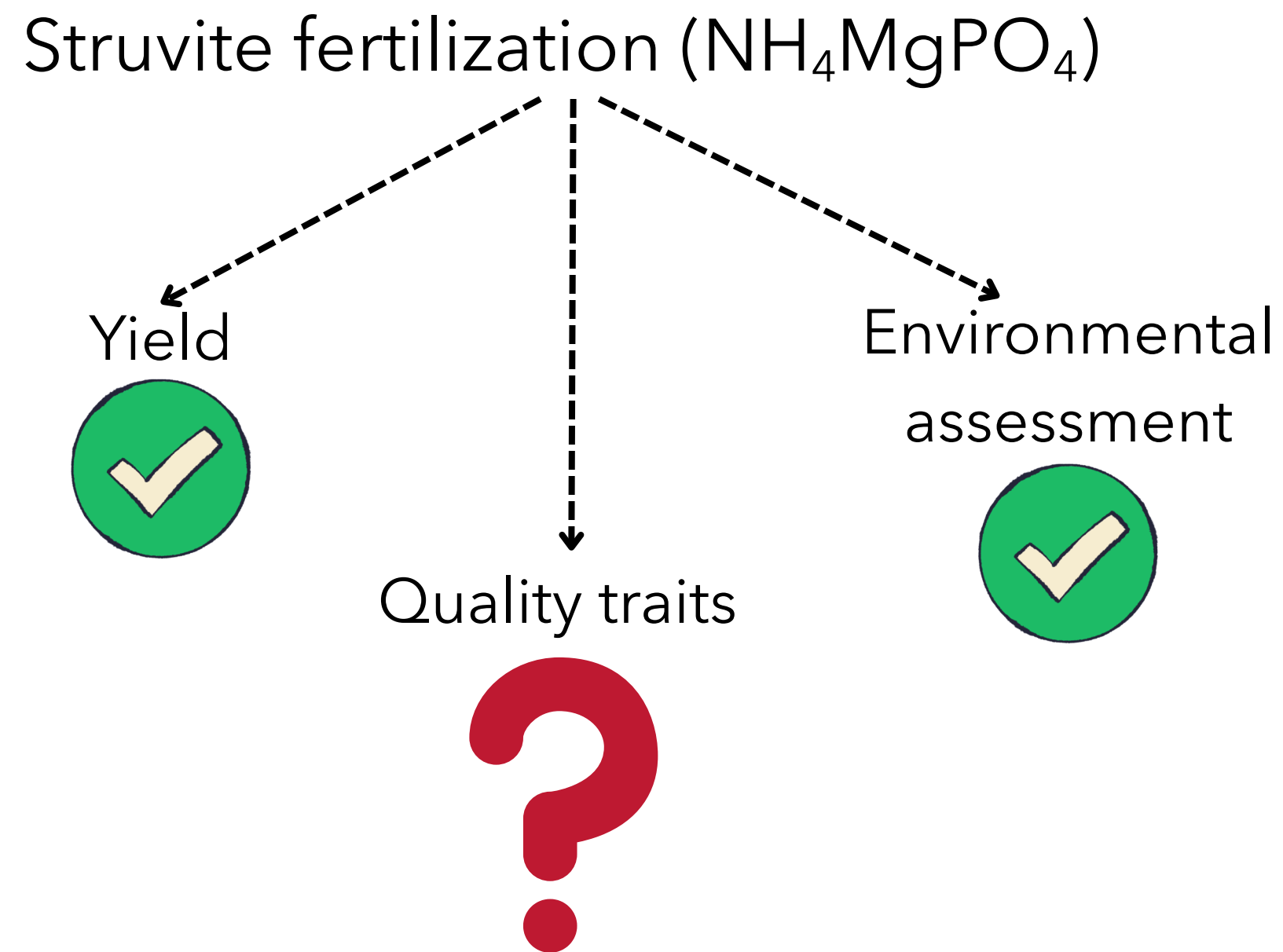


Chapter 3:

The effect of struvite fertilization on tomato soluble solid contents, acidity, physiological disorders and consumers' preferences



Introduction



Research questions and objectives

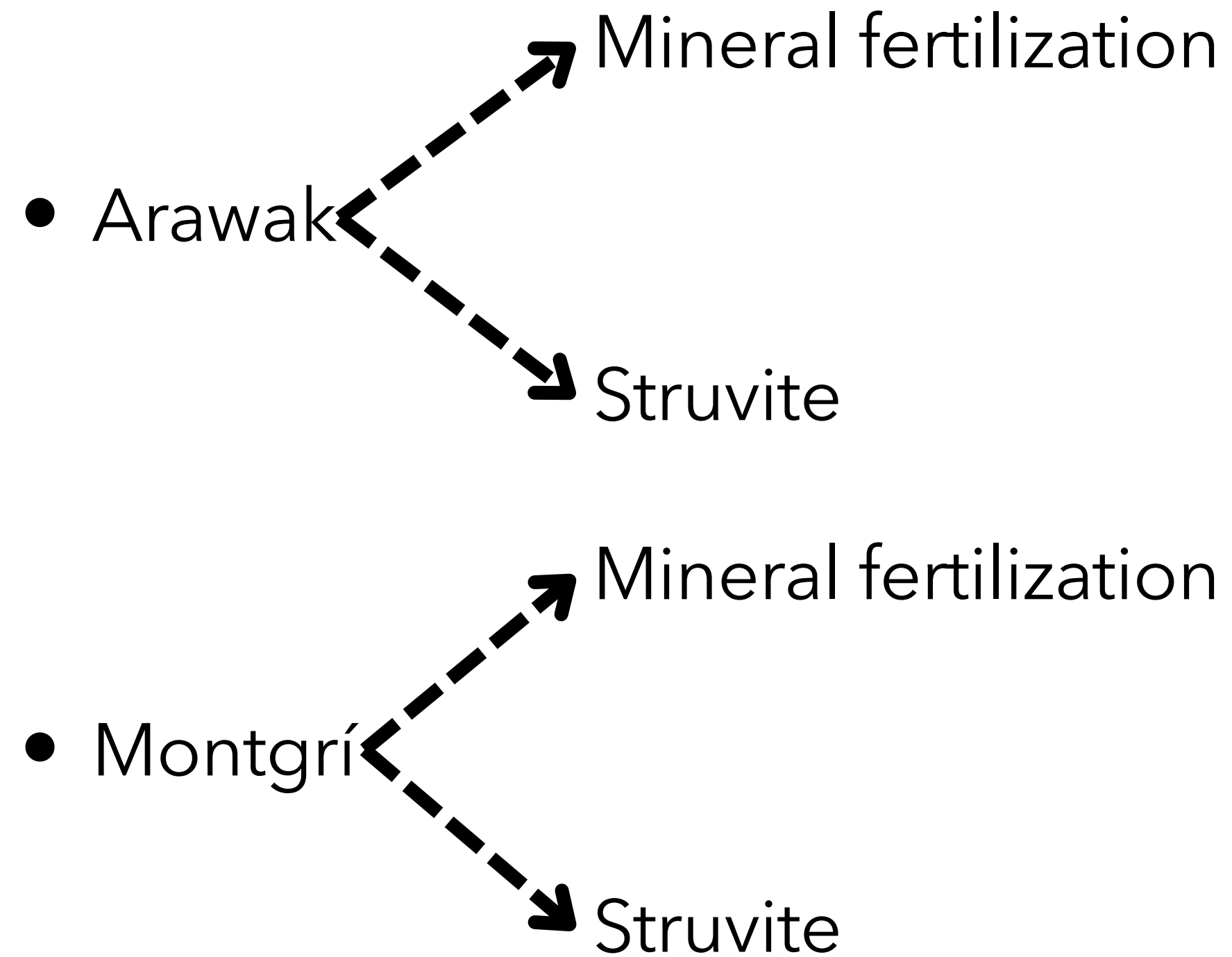
Research question n.2:

How does struvite fertilization influence quality traits and consumer preferences in hydroponic tomato production?

Research objective n.2:

Test the effect of struvite fertilization by evaluating fruit's soluble solid contents (SSC), titratable acidity (TA), nutrient concentrations, incidence of physiological disorders, and consumer preferences?

Tomato cultivation



Soluble solid contents (SSC) and titratable acidity (TA) measurements

- Fruit juice analysed with a pocket Brix and acidity meter
- One-way ANOVA followed by Tukey post-hoc



Physiological disorders: blossom-end rot and greenback

- Visual evaluation
- Incidence evaluated with logistic regression models with binomial distribution followed by Tukey post-hoc



Blind taste test

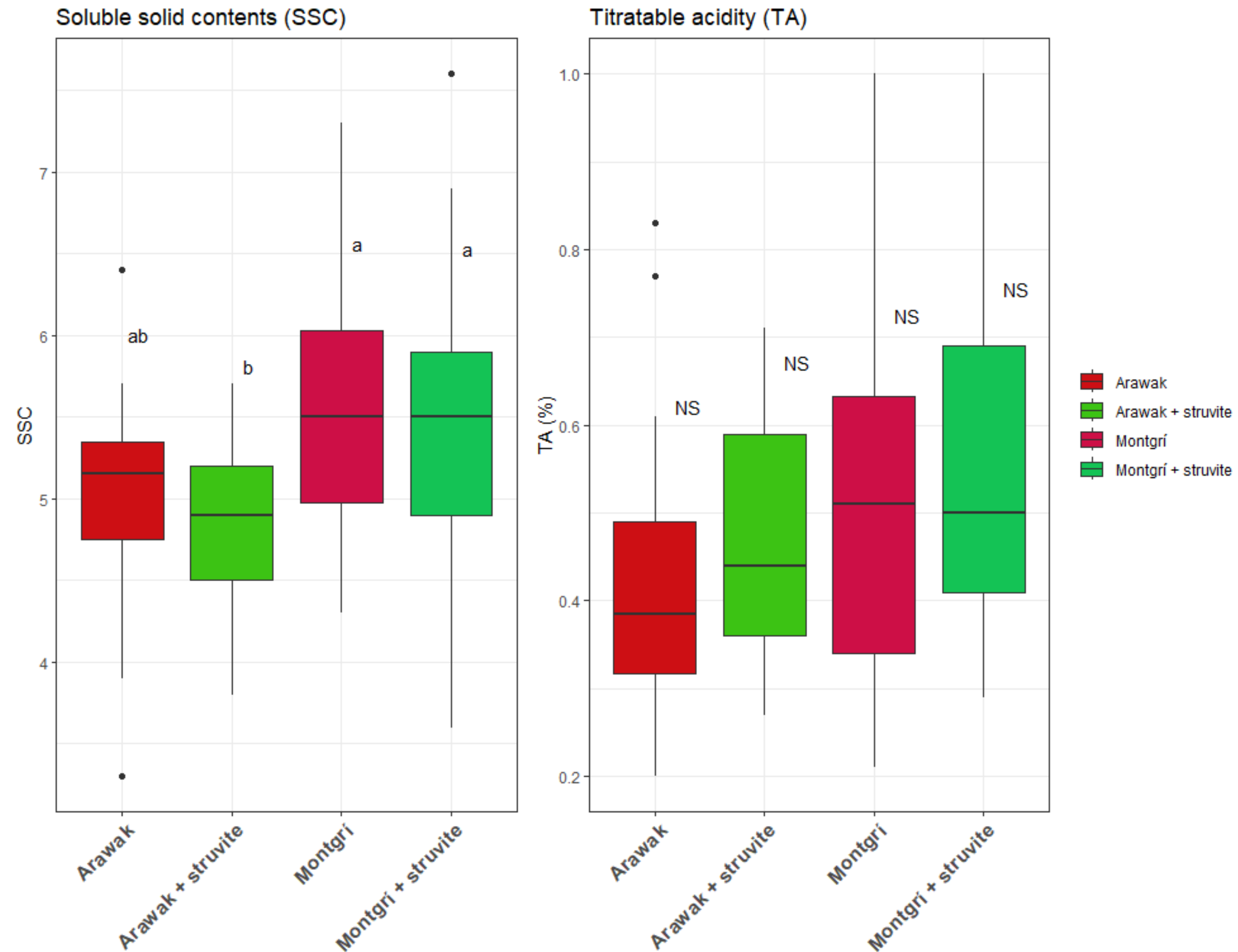
- 141 participants
- Samples labelled to avoid bias
- Five-point Likert scale

Results analysed with:

1. Shapiro-Wilk test ($p < 0.05$)
2. Kruskal-Wallis test ($p < 0.05$)
3. Post-hoc comparison using the Dunn test with Bonferroni correction



Results



Results

Treatment	Arawak + mineral fertilization	Arawak + struvite	Montgrí + mineral fertilization	Montgrí + struvite
Percentage of fruits with BER (%)	14.9	16.3	17.7	17.2
Significant differences	NS	NS	NS	NS
Percentage of fruits with GB (%)	6.3	3.4	30.6	22
Significant differences	b	a	d	c

Results



Conclusions

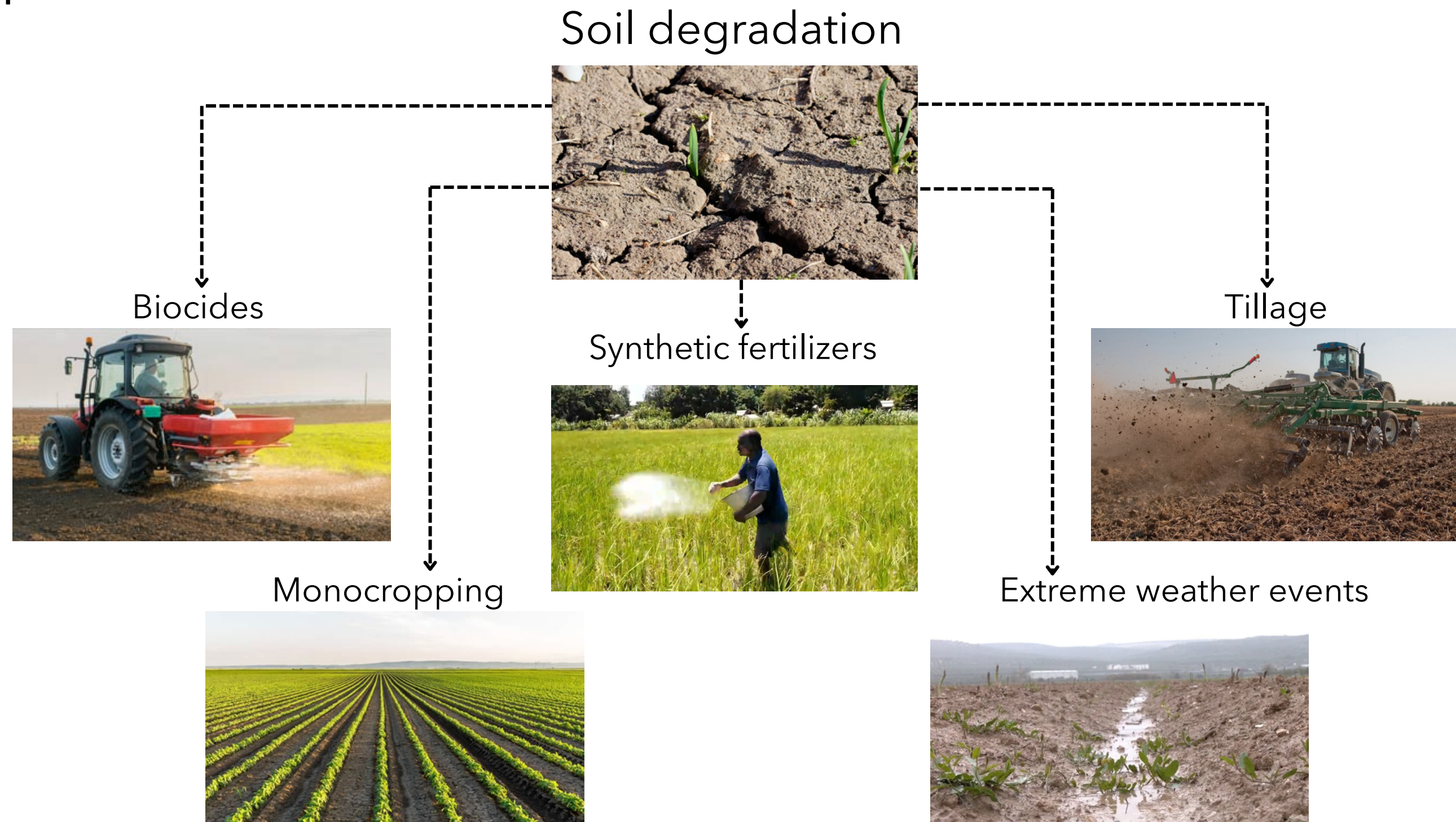
- SSC and TA accumulation were not restricted by struvite
- BER appearance was not increased by struvite
- Greenback appearance was lower on struvite-grown tomatoes
- Participants of the survey showed preference for struvite-grown tomatoes



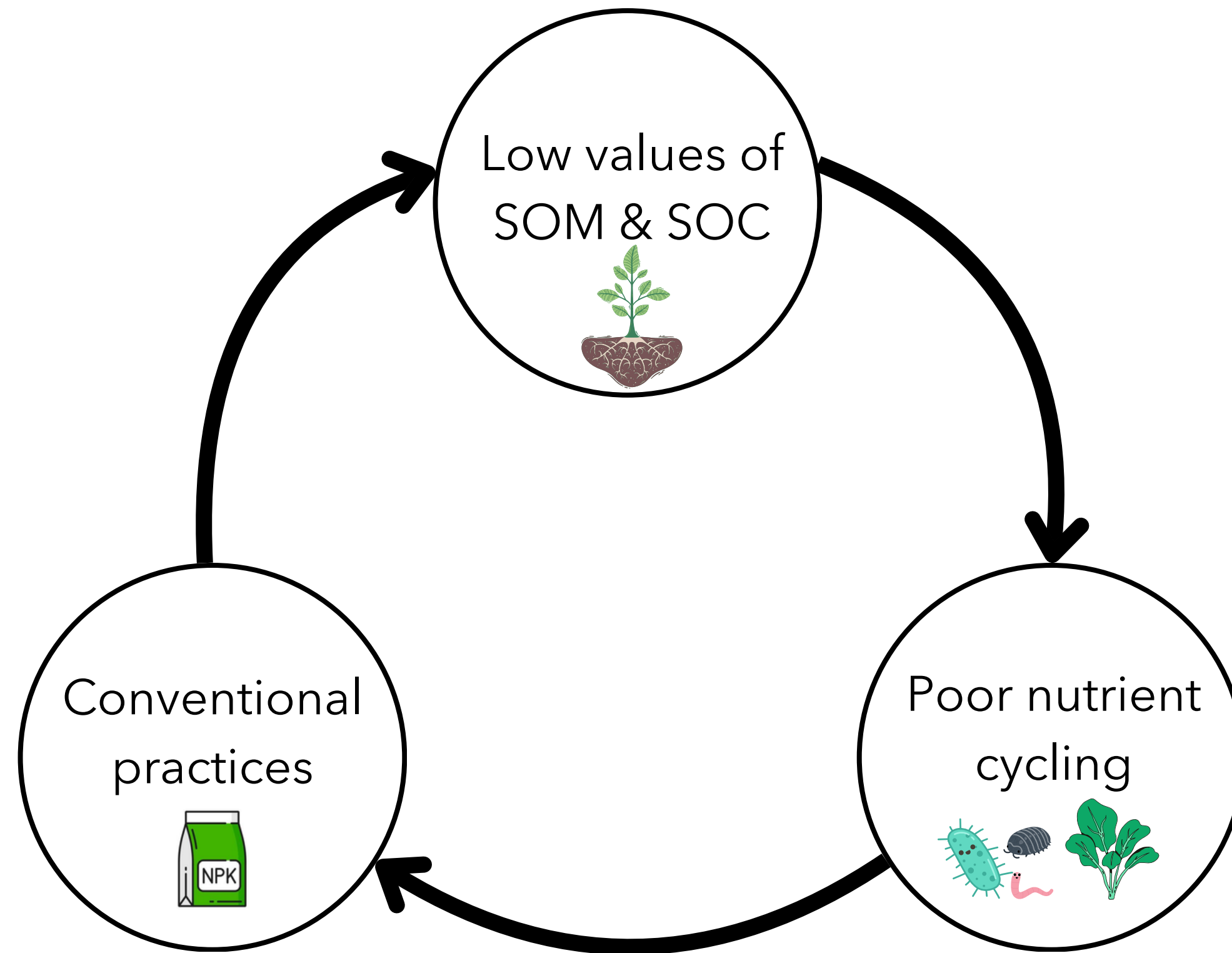
Chapter 4:
Applying recovered nutrients
and pruning waste to enrich
and regenerate agricultural
soils in urban agriculture:
effects on emissions and yield
of spinach and sweet potato



Introduction



Soil degradation process



The solution to soil degradation

- Carbon-rich residues can restore SOC and nutrient cycling
- Ramial chipped wood (RCW) from municipal pruning waste can be used
- RCW could limit growth and promote gaseous emissions



Research questions and objectives

Research question n.3:

What are the production and environmental implications of applying recovered nutrients for soil-based spinach and sweet potato cultivation?

Research objective n.3:

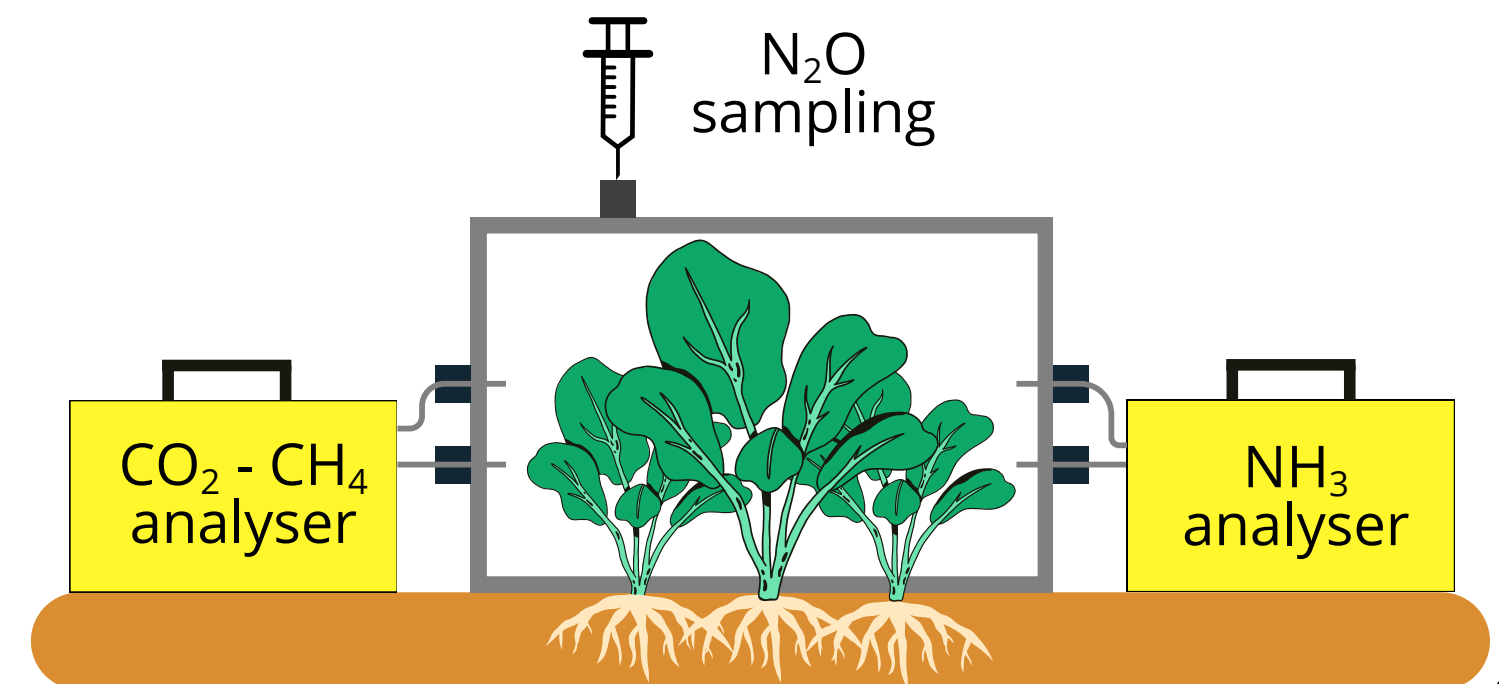
Evaluate crop yield, gaseous emissions, and soil health in spinach and sweet potato grown with RCW, struvite, or compost in a peri-urban field.

Methods

- Spinach and sweet potato cultivation
- CO_2 , CH_4 , N_2O , and NH_3 emissions through static chambers
- Analysis of soil samples
- Statistical analysis

Fertilization:

- Mineral fertilization
- Struvite + organic nitrogen
- Compost
- Ramial chipped wood (RCW)
- RCW + organic nitrogen

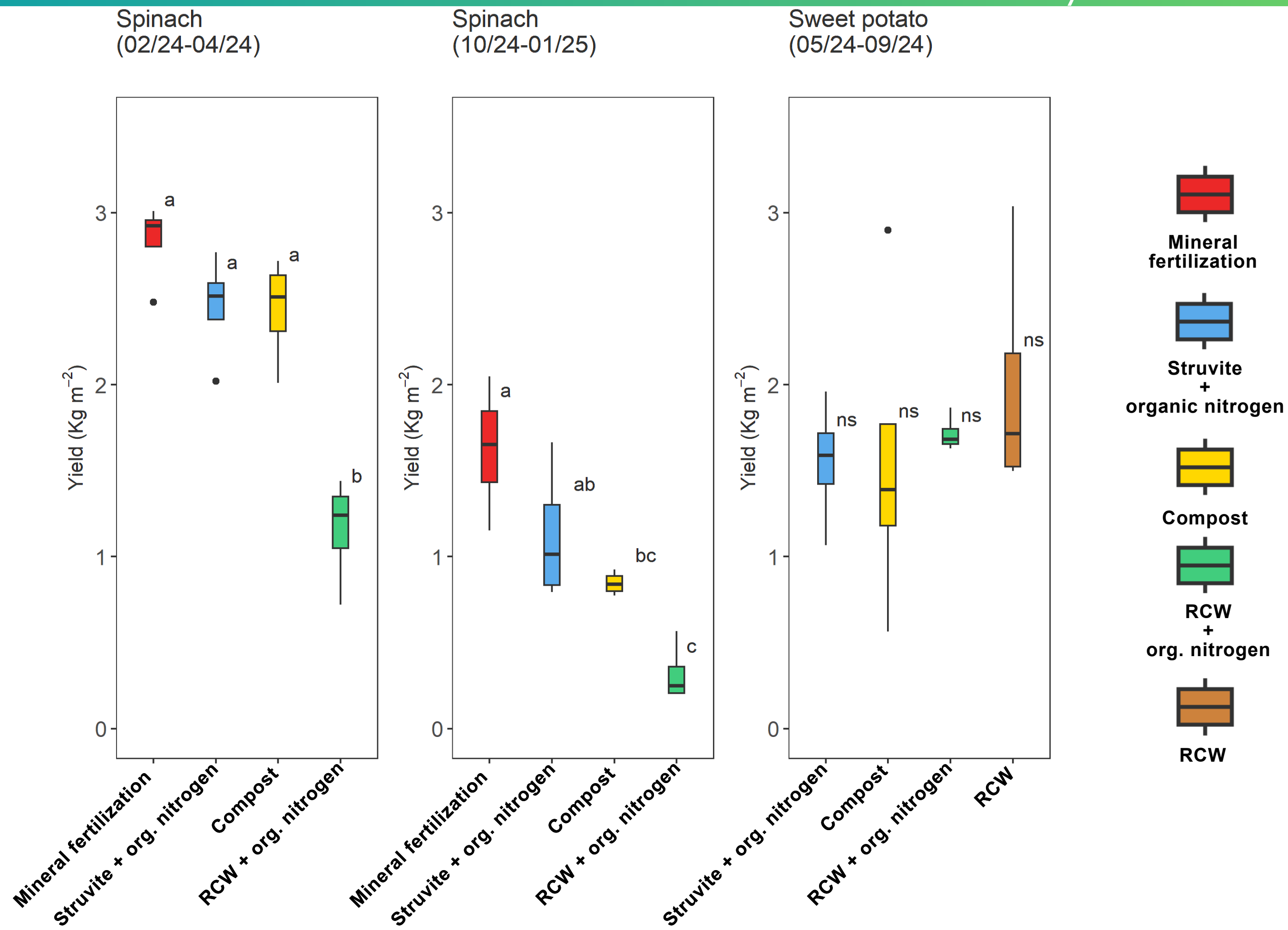


On-site measurements of CO₂, CH₄, N₂O and NH₃

- 1-3 times a week from Feb. 2024 until Jan. 2025
- CO₂, CH₄ and NH₃: analysed with two portable laser analysers
- N₂O: gas samples collected in flasks and analysed with a gas chromatographer

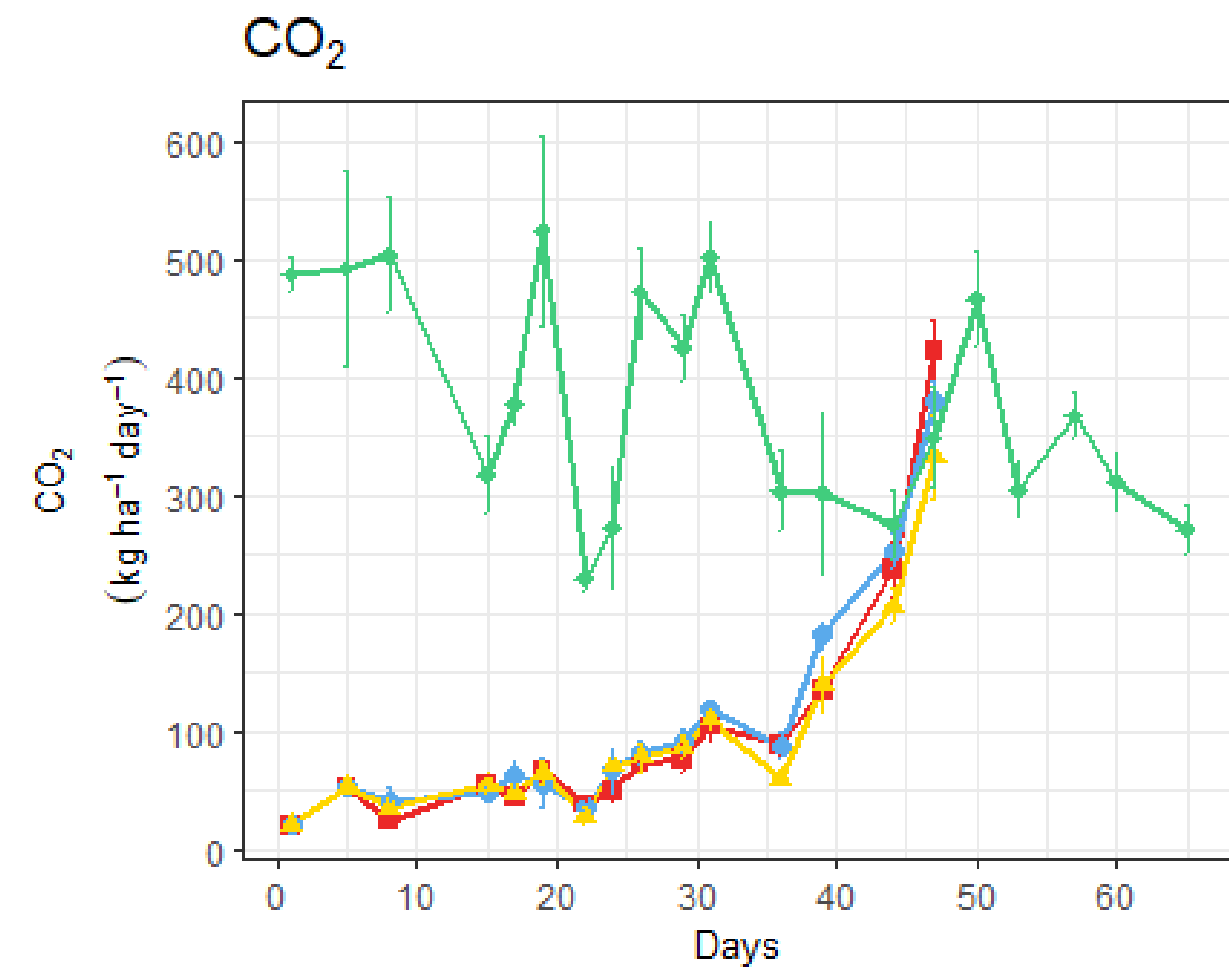


Results

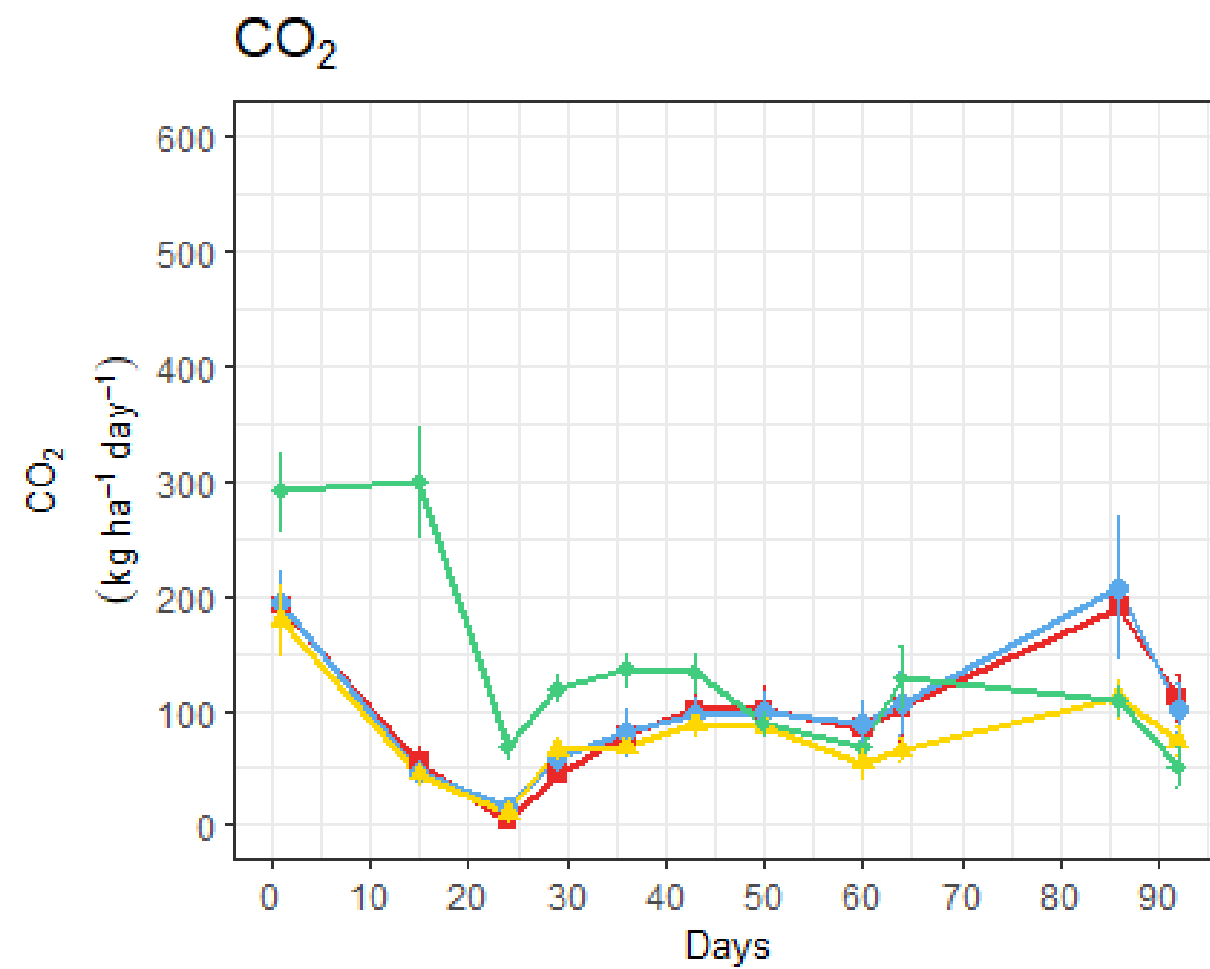


Results

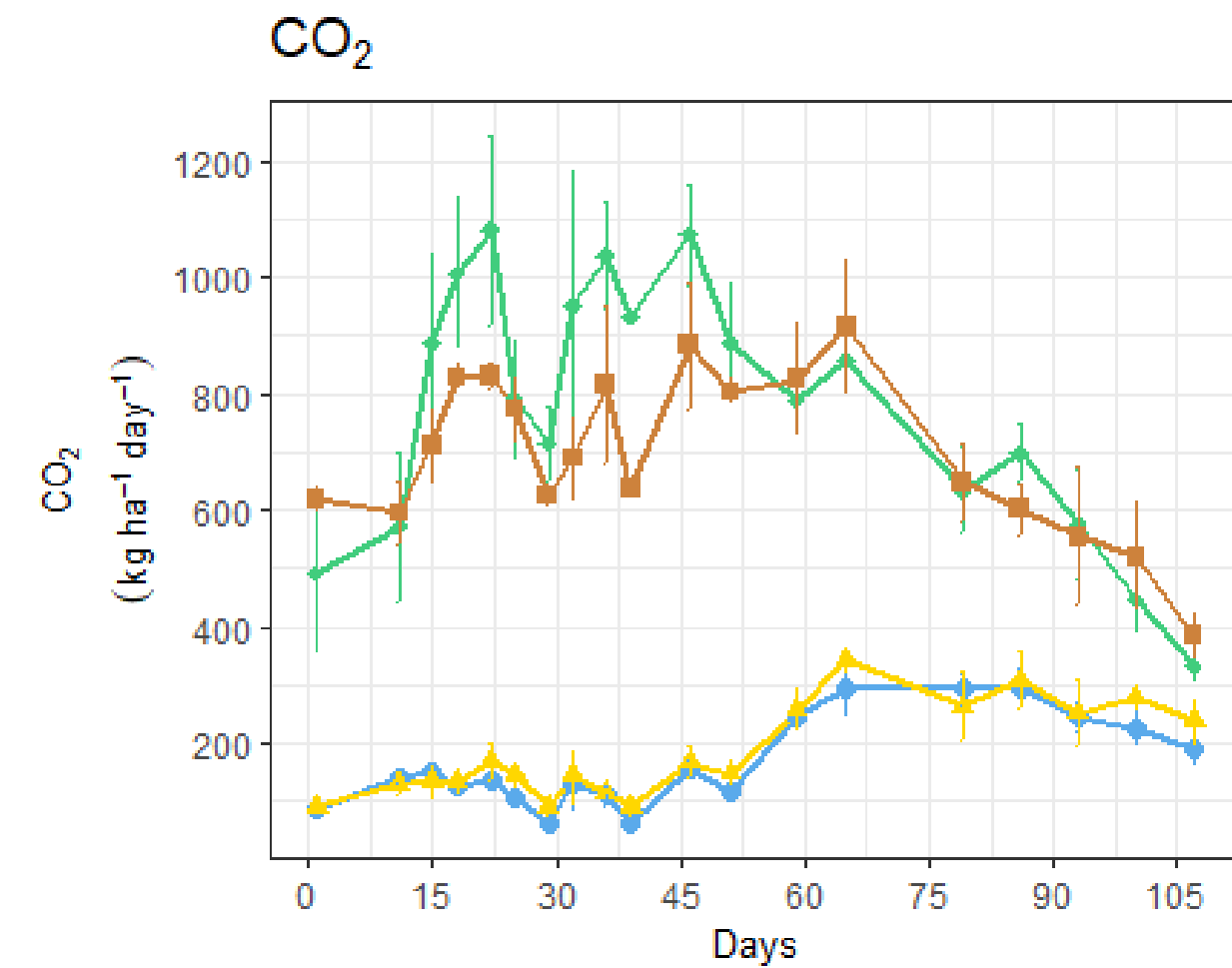
Spinach cycle (Feb. - Apr. 2024)



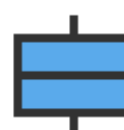
Spinach cycle (Oct. 2024 - Jan. 2025)



Sweet potato cycle (May - Sept. 2024)




Mineral
fertilization


Struvite
+
organic nitrogen

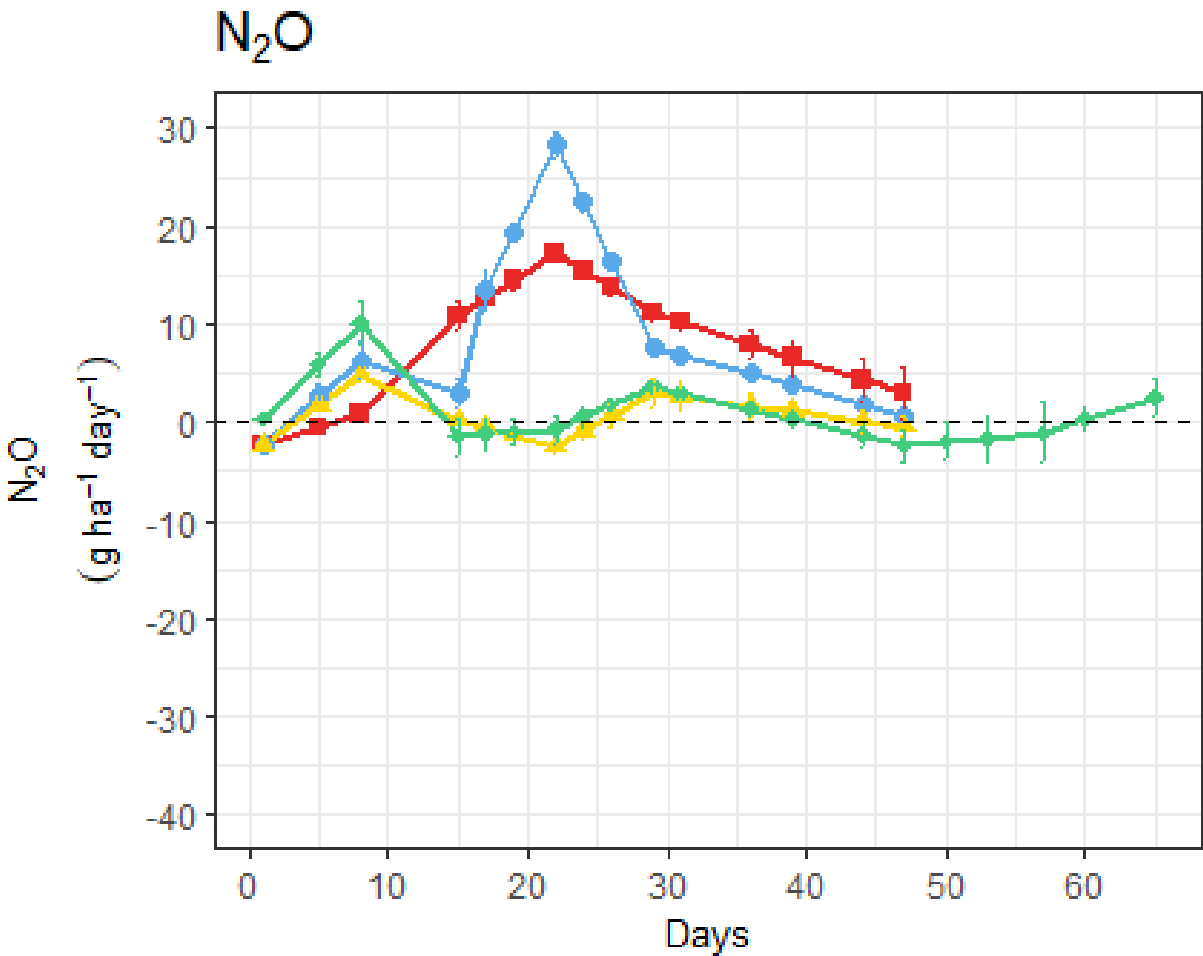

Compost


RCW
+
org. nitrogen

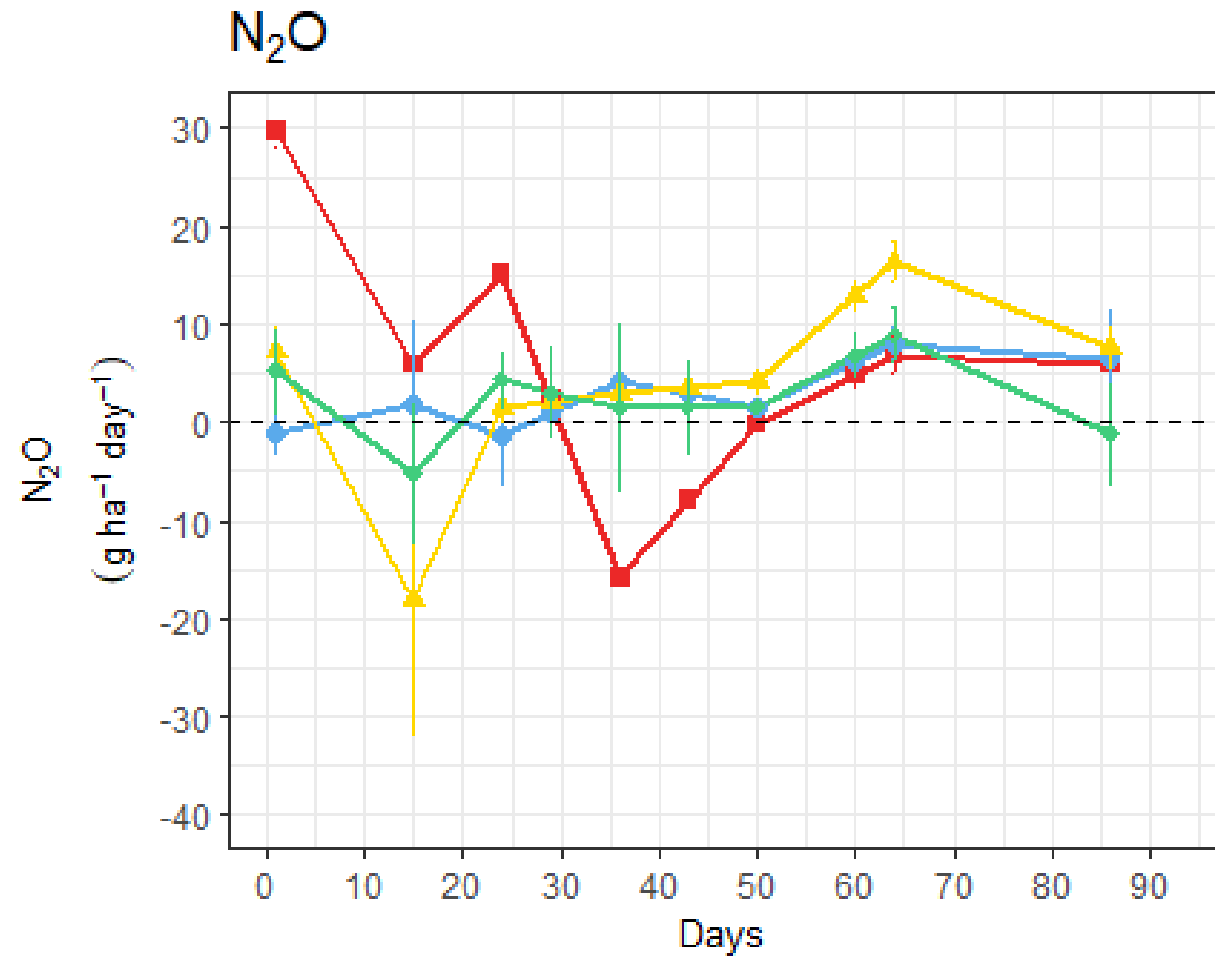

RCW

Results

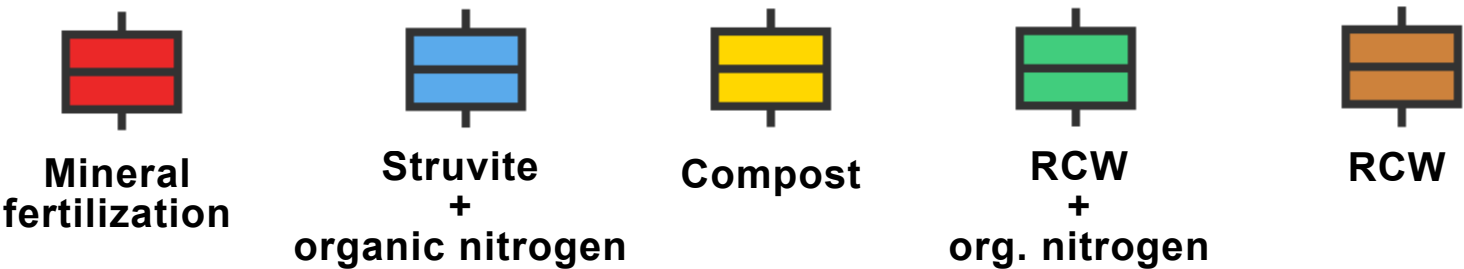
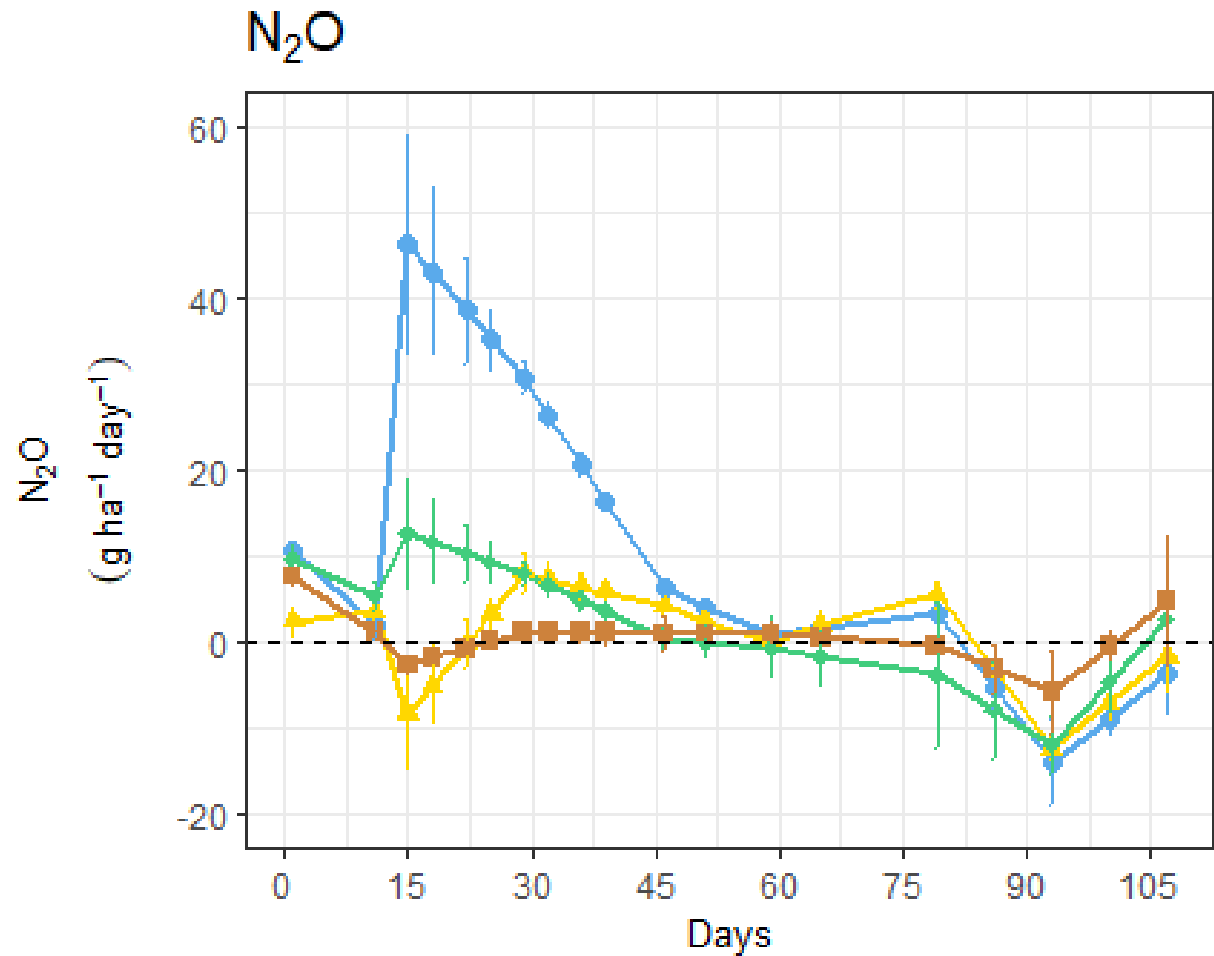
Spinach cycle (Feb. - Apr. 2024)



Spinach cycle (Oct. 2024 - Jan. 2025)



Sweet potato cycle (May - Sept. 2024)



Impacts of recovered nutrients on production and soil health

- Struvite and compost treatments maintained high productivity
- RCW incorporation boosted sweet potato production
- RCW increased SOC (+80.1%) and nutrient stocks after 11 months



Gaseous emissions behaviour

- RCW increased short-term CO_2 fluxes that declined over time
- CH_4 and NH_3 emissions were minimal due to drip irrigation and nature of the fertilizers
- RCW and compost generated lower N_2O emissions



N₂O emissions (first spinach cycle)

Nitrogen applied (kg ha ⁻¹)		Cumulative N ₂ O emissions (kg ha ⁻¹)		Measured EF	IPCC EF
↓		↓		↓	↓
Mineral fertilization:	73.4		0.36	0.31%	1%
Struvite + org. N:	73.5		0.38	0.33%	1%
Compost:	352.2		0.04	0.007%	1%
RCW:	2316		0.07	0.002%	1%

Conclusions

- High productivity was obtained with struvite and compost fertilization
- Sweet potato is the ideal crop after RCW incorporation
- RCW and compost mitigate N₂O emissions
- RCW enhances SOC (+80 - 117%) and nitrogen stocks (+40 - 82%) unlike other treatments



This chapter is based on the journal paper:

Chapter 5: Soil regeneration and horticulture production with ramial chipped wood (RCW): guidelines for successful yields

Journal: Zenodo
DOI: 10.5281/zenodo.15736567



Introduction

- Develop a series of guidelines based on the results of **Chapter 4**
- NUTRISOIL: Healthy Soil for Urban Agriculture through Nutrient and Carbon Circularity



Research questions and objectives

Research question n.4:

How can RCW or other carbon-rich residues be promoted to regenerate degraded peri-urban soils and ensure sustainable crop production?

Research objective n.4:

Develop practical guidelines for farmers, stakeholders and municipalities for RCW or other carbon-rich residues implementation in peri-urban agriculture.

Assessing the state of soil

- Visual evaluation
- The slake test
- Soil test



RCW incorporation

- Initial dose of 100 - 150 ton ha⁻¹ (C/N ratio: 40 - 70)
- Biomass from plane trees (*Platanus occidentalis* L.)
- Size: < 5 cm in length and 3 cm in diameter
- Incorporation with a rotary tiller at 20 cm depth



Crop selection

- Sweet potato (cv. “Beauregard” and “O’ Henry”)
- Avoid nitrogen-demanding crops
- Faba bean in colder climates



Methods to maintain high levels of SOC

- Compost: increases OM, feeds the microbiota
- Manure: increases SOC and soil stability
- Cover crops: increases SOM, soil structure and nutrient contents
- Reduced or no-till practices: preserve SOC contents



Guidelines for municipalities and stakeholders

- Invest in shredders, transport vehicles and storage facilities
- Assist the farmers in RCW or other C-rich residues incorporation
- Promote RCW adoption with economic compensations or marketing campaigns to support the farmers



Regulatory barriers to recovered nutrient use

- **Nitrates Directive (91/676/EEC):** limits land application of organic-derived nitrogen to $170 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in nitrate-vulnerable zones, while no limits are set for synthetic fertilizers.
- **Waste Framework Directive (2008/98/EC):** absence of end-of-waste criteria in the European Union keeps compost classified as waste, increasing administrative and logistical costs compared to synthetic fertilizers.

Conclusions

- RCW incorporation is most effective with N-fixing crops
- SOC levels can be preserved with little or no-tillage combined with the incorporation of C-rich residues
- Farmers need support to encourage RCW implementation



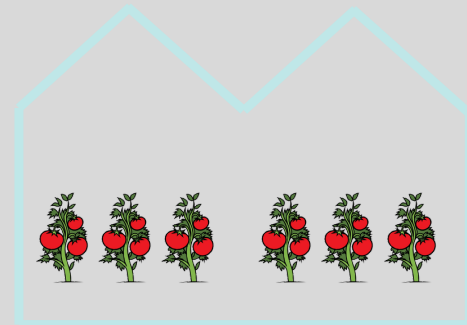
Chapter 6: General discussion



Chapter 1: Introduction

Chapter 2

Hydroponic tomato
in an i-RTG



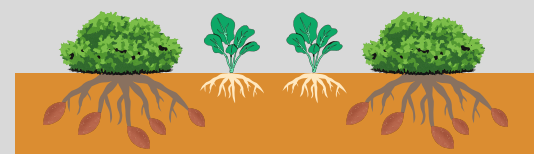
RQ1: What are the key agronomical, technical and environmental drivers of productivity and sustainability in long-term hydroponic tomato cultivation in an i-RTG?

Chapter 3

RQ2: How does struvite fertilization quality traits and consumer preferences in hydroponic tomato production?

Chapter 4

Open-field cultivation of
spinach and sweet potato in a
peri-urban field



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Chapter 7: Conclusions

RQ5: Can recovered nutrients replace mineral fertilizers without compromising productivity, quality and sustainability for horticultural production?

Research questions and objectives

Research question n.5:

Can recovered nutrients replace mineral fertilizers without compromising productivity, quality and sustainability for horticultural production?

Research objective n.5:

Discuss the feasibility of recovered nutrients implementation for urban and peri-urban horticulture by generally discussing the findings of this dissertation and past literature.

Struvite adoption for hydroponic tomato cultivation

- 100 g of struvite per plant placed in the substrate promotes yield and reduces environmental impacts
- To sustain productivity, polycarbonate sheets should be changed every 4 - 6 years



Struvite adoption for hydroponic tomato cultivation

- Struvite does not negatively affect SSC or TA accumulation
- Struvite fertilization does not promote physiological disorders appearance
- Participants of the survey showed preference for struvite-grown tomatoes



Recovered nutrients impacts for soil-based cultivation

- Compost and struvite ensured high yields for both crops
- RCW boosted sweet potato productivity while increasing SOC (80.1 - 116-6%)
- Organic fertilizers mitigated N₂O emissions
- RCW application promoted short-term CO₂ emissions



Chapter 7: Conclusions



Research question n.1:

What are the key agronomical, technical and environmental drivers of productivity and sustainability in long-term hydroponic tomato cultivation in an i-RTG?

- Ensuring optimal radiation with regular substitution of polycarbonate sheets (4 to 6 years)
- Adjusting the nutrient solution based on the phenological stage of the plant
- Applying a dose of 100 g per plant of struvite in the substrate

Research question n.2:

How does struvite fertilization influence quality traits and consumer preferences in hydroponic tomato production?

- Struvite fertilization promotes SSC and TA synthesis
- Struvite fertilization do not promotes physiological disorders appearance
- Participants of the panel test preferred struvite-grown tomatoes

Research question n.3:

What are the production and environmental implications of recovered nutrients for soil-based spinach and sweet potato cultivation?

- Struvite and compost promoted spinach and sweet potato production
- RCW incorporation increased sweet potato production while restricting spinach growth
- RCW increased SOC, nitrogen and other macronutrients stocks
- RCW and compost minimized N₂O volatilization

Research question n.4:

How can RCW or other carbon-rich residues be promoted to regenerate degraded peri-urban soils and ensure sustainable crop production?

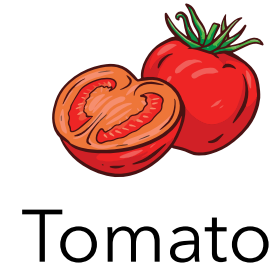
- Pair RCW incorporation with sweet potato or other N-fixing crops
- Maintain high levels of SOC with minimal tillage and periodic carbon inputs
- Assist farmers in collecting, shredding and applying RCW
- Facilitate recovered nutrients adoption with targeted policies

Research question n.5:

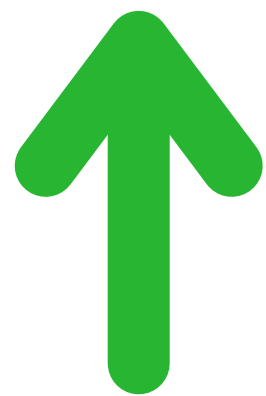
Can recovered nutrients replace mineral fertilizers without compromising productivity, quality and sustainability for horticultural production in soilless and open-field systems?

Yes, but only when applied with appropriate management and crop-specific strategies

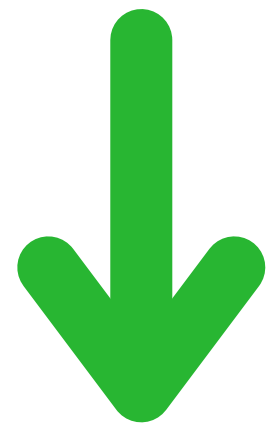
100 g plant⁻¹ of struvite



140 g plant⁻¹ of struvite



High yield and quality
(7.1 kg plant⁻¹)



Low
environmental
impact
(0.94 kg CO₂ eq.)



Low yield
(1.3 kg plant⁻¹)

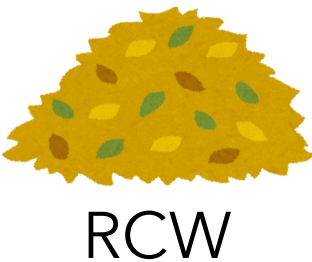


High
environmental
impact
(4.76 kg CO₂ eq.)

Research question n.5:

Can recovered nutrients replace mineral fertilizers without compromising productivity, quality and sustainability for horticultural production in soilless and open-field systems?

Yes, but only when applied with appropriate management and crop-specific strategies



1.12 - 2.45 kg m⁻²

1.55 kg m⁻²

0.38 - 0.92 kg ha⁻¹

0.84 - 2.44 kg m⁻²

1.56 kg m⁻²

0.04 - 0.07 kg ha⁻¹

0.32 - 1.16 kg m⁻²

1.72 - 1.99
kg m⁻²

0.03 - 0.21 kg ha⁻¹

SOC

-0.40 - 8.67%

SOC

+0.31 - 8.27%

SOC

+80 -116%

Conclusions

The results obtained from two contrasting settings and different kind of crops showed how these techniques can be implemented for commercial production, due to their ability to enhance productivity, increase quality traits, minimize environmental impacts and promoting ecosystem benefits.

Thank you!

