Formulation and Testing of a Nutrient Solution Derived From Organic Waste to Support Hydroponic Crop Production for Space Applications

Icíar Giménez de Azcárate Bordóns[1], Astrid Oberson[1], Matías Chávez[2], Shelby Buckley[1] and Emmanuel Frossard[1]

[1] Department of Environmental Systems Sciences, ETH Zürich
[2] Independent researcher

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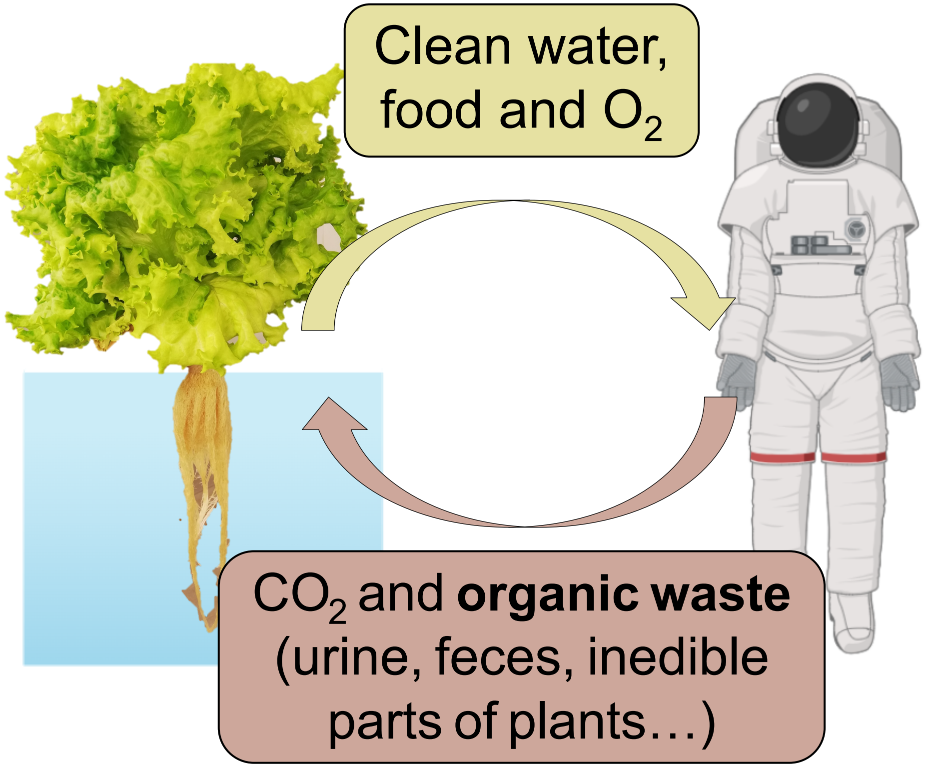
Introduction: Current and future plant nutrition for space

Plants are currently grown in Space with controlled-release fertilizers from Earth adapted to plant variety

28-day-old lettuce growing in a prototype v flight pillow. Image Credit: NASA/Gioia Massa.



MELiSSA loop (or any BLSS):

- Recover nutrients from **organic waste** streams
- Ensure nutrient availability to plants
- Precisely dose nutrients – avoid waste of resources

Challenges: Organic waste materials have **different nutrient composition**, chemical speciation and toxic compounds (e.g, NaCl)

Objective and materials

Create a **macronutrient-complete** and **balanced** nutrient solution for lettuce in hydroponics, using complementary waste materials from the MELiSSA loop.

Plants need >1 g (N, P, K, Ca, Mg & S) kg^{-1} DM, taken up in ionic water-soluble forms

Synthetic nitrified urine* (liquid) ⬆ N, P & S

Soybean residues (solid) ⬆ Ca, Mg & K → Water extraction (6.6 g DM L^{-1}), filtration (1.4 µm) & pasteurization → Soybean extract

Stems, leaves & pods in harvested proportions

Control nutrient profile - ½ Hoagland nutrient solution (common for plant physiology studies)

* formulation adapted from Udert and Watcher 2012 by Bonvin, et al. 2015

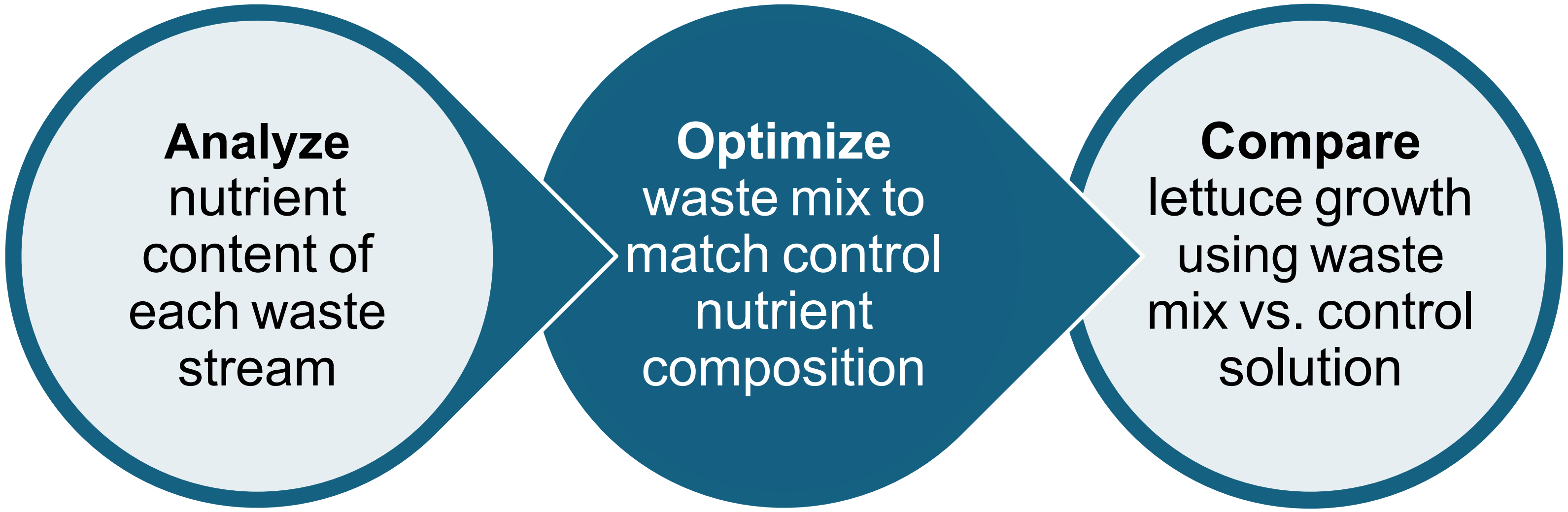
Method overview

Analyze nutrient content of each waste

Optimize waste mix to match control nutrient composition

Compare lettuce growth using waste mix vs. control solution

Method overview



Method overview

Generic optimization model based on **least squares method** using 2 waste materials and 7 nutrients

Mathematical approach

$\overline{X}_1$= Nitrified urine → $N\text{-}NH_{4\,1}$, $N\text{-}NO_{3\,1}$, P_1, K_1, Ca_1, Mg_1, S_1 (mg nutrient $L^{-1}\,\overline{X}_1$) ⟶ $v_1 = L\,\overline{X}_1\,L^{-1}$ nutrient solution

$\overline{X}_2$= Soybean extract → $N\text{-}NH_{4\,2}$, $N\text{-}NO_{3\,2}$, P_2, K_2, Ca_2, Mg_2, S_2 (mg nutrient $L^{-1}\,\overline{X}_2$) ⟶ $v_2 = L\,\overline{X}_2\,L^{-1}$ nutrient solution

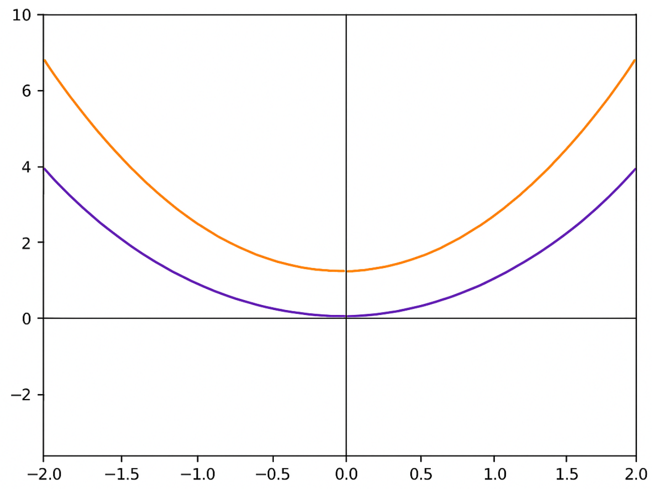
$\overline{X}_t$= Target nutrient solution → $N\text{-}NH_{4\,t}$, $N\text{-}NO_{3\,t}$, P_t, K_t, Ca_t, Mg_t, S_t (mg nutrient $L^{-1}\,\overline{X}_t$)

$\overline{X}_1 \cdot v_1 + \overline{X}_2 \cdot v_2 = \overline{X}_t$; $F(v_1, v_2) = |\overline{X}_1 \cdot v_1 + \overline{X}_2 \cdot v_2 - \overline{X}_t|^2$ = 0 (if perfect), min (if realistic)

$\underset{v_1,\, v_2 \geq 0}{\arg\min}\; F(v_1, v_2)$

Numerical approach

1. Start from random v_1, v_2
2. Follow the gradient to find the minimum error to $\overline{X}_t$



Method overview

Analyze nutrient content of each waste stream

Optimize waste mix to match control nutrient composition

Compare lettuce growth using waste mix vs. control solution

- 28-day growth of lettuce (*Lactuca sativa* var. Frillice) in hydroponics
- Waste mix vs. control (½ Hoagland) nutrient solutions
- 3 replicates / experimental unit = 5 lettuces in 30 L of nutrient solution
- Randomized block design

Results - Optimized waste mix solution

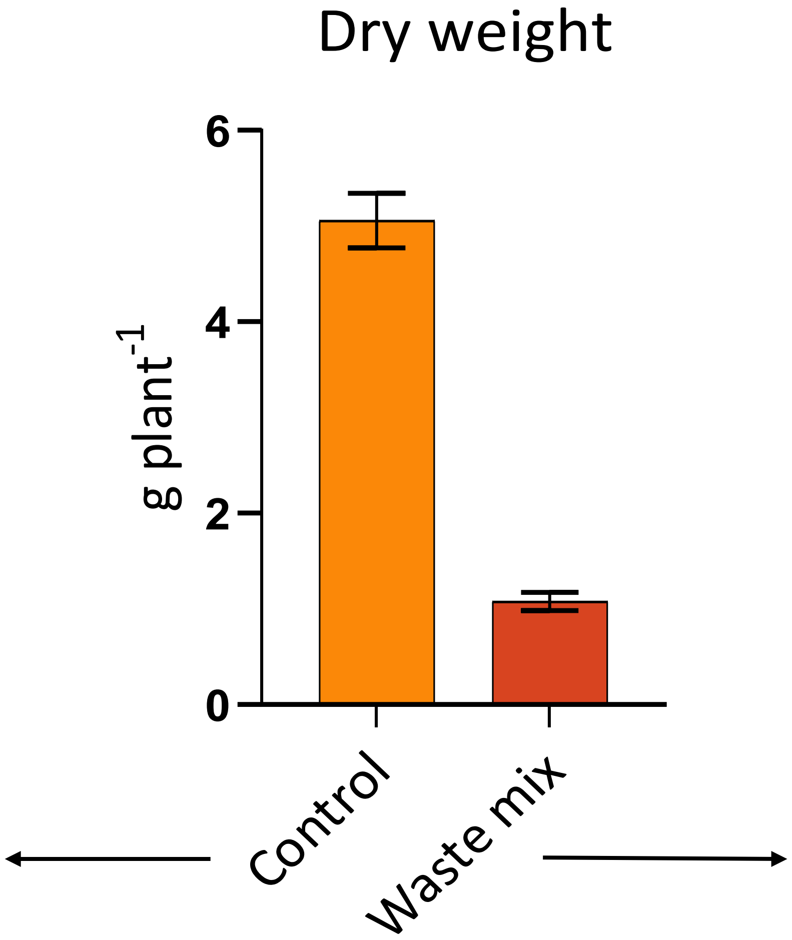
Nutrient	Waste mix = 590 mL L^{-1} solution + 13 mL L^{-1} solution		½ Hoagland
	Optimization result (mg L^{-1})	Error (mg L^{-1})	Requirements (mg L^{-1})
N_{min}	94.6	-10.4	105
P	16.5	+1.0	15.5
K	136.5	+19.5	117
Ca	46.4	-33.6	80.2
Mg	13.8	-10.5	24.3
S	14.4	-17.8	32.2
$N\text{-}NO_3 : N\text{-}NH_4$	1.1		14

Macronutrient-complete?

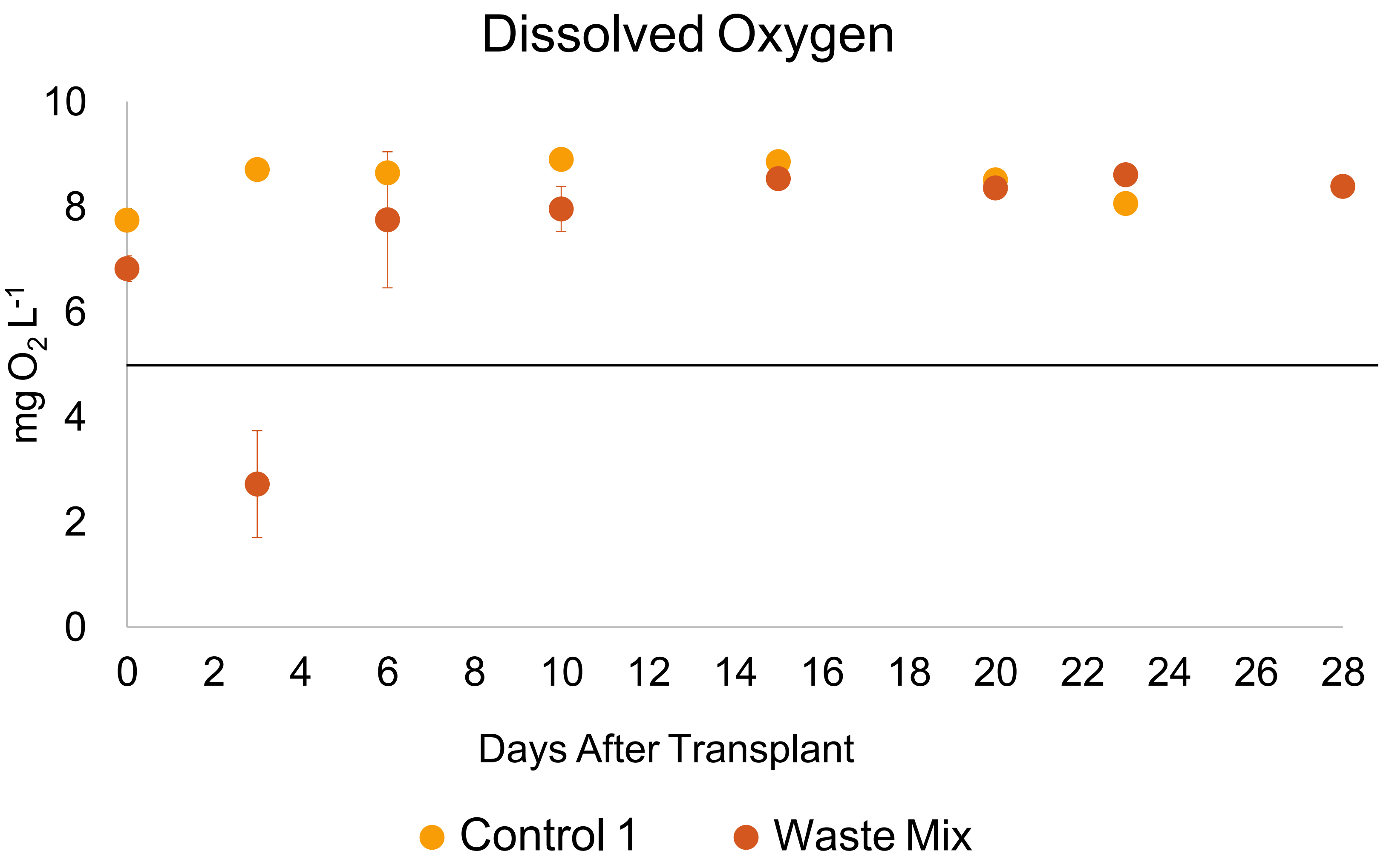
Balanced?

in waste mix ↓ $N\text{-}NO_3 : N\text{-}NH_4$ ↓ Mg, Ca, & S

Results: Dry weight decrease in waste mix treatment

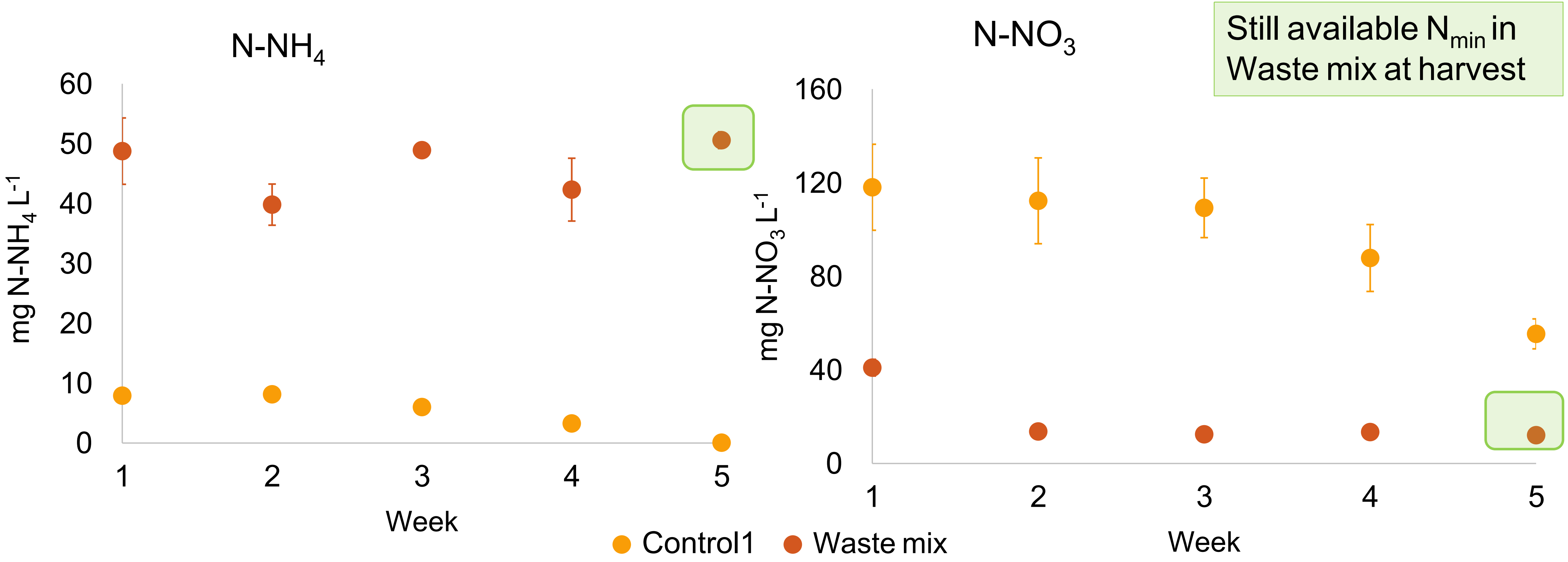


Results: Early oxygen stress is a trigger but not the sole cause of growth limitation



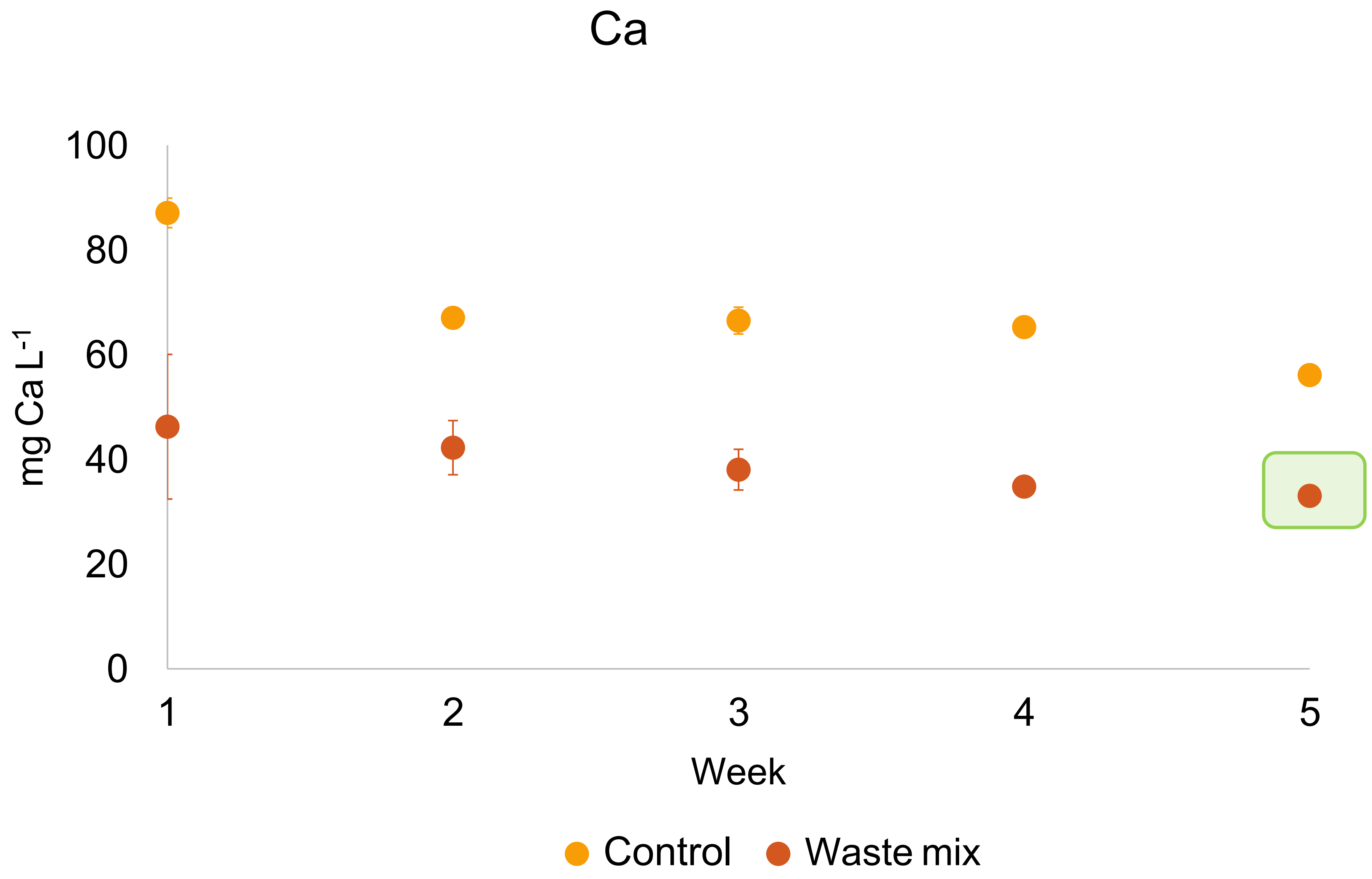
< 5 mg O_2 L^{-1} can be detrimental

Results: Ruling out nutrient limitation (example for N_{min})



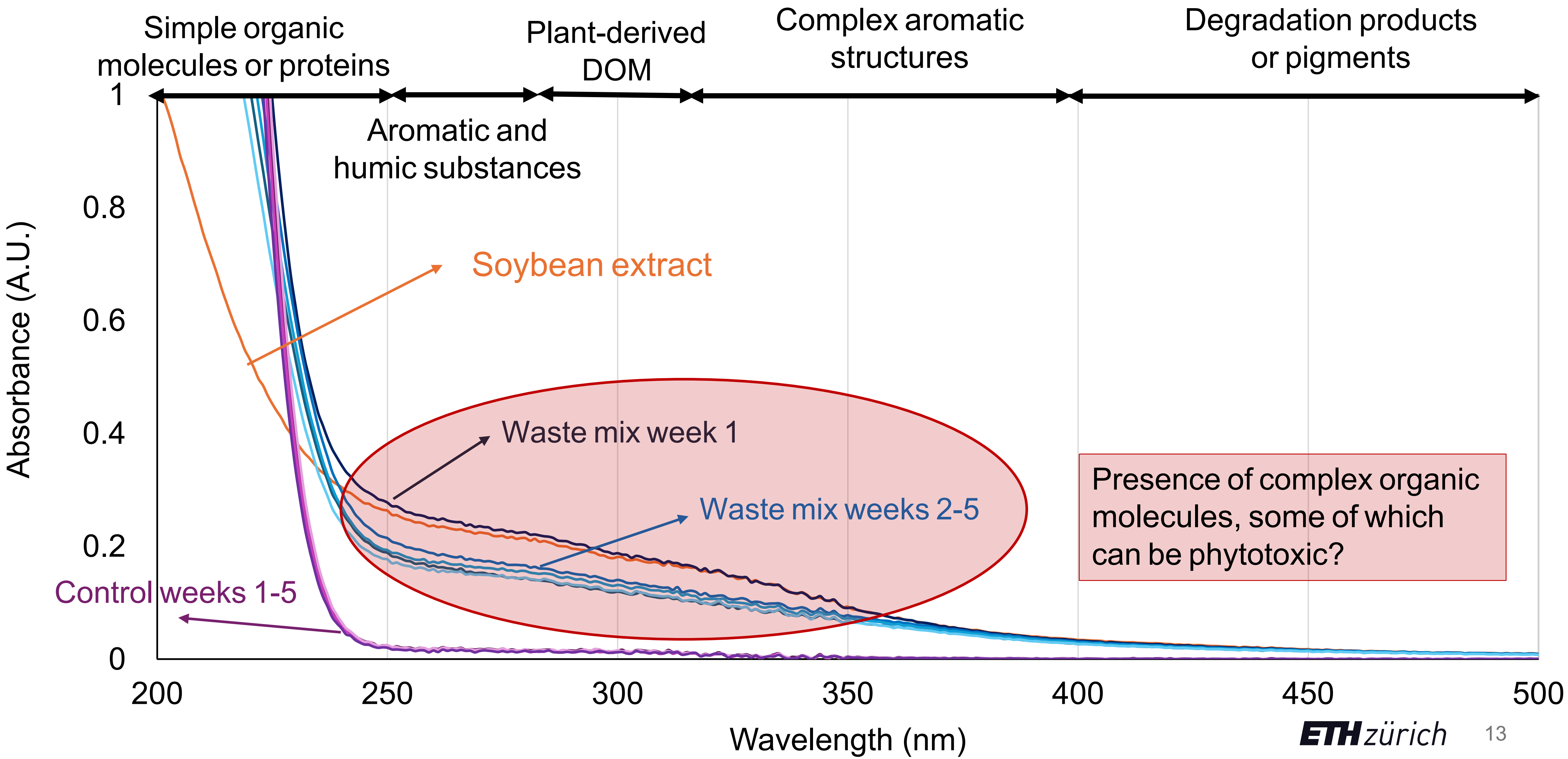
Still available N_{min} in Waste mix at harvest

Results: Ruling out nutrient limitation (example for Ca)



Still available Ca in Waste mix at harvest

Results: Organic matter speciation (qualitative UV-VIS)



Presence of complex organic molecules, some of which can be phytotoxic?

Concluding remarks

- It is **possible** to create a **macronutrient-complete waste-based nutrient solution** for hydroponic lettuce growth from MELiSSA waste streams
- We created a **generic optimization model** to precisely calculate how to mix different waste materials to match a target nutrient concentration
- **Plant growth reduction** in waste mix treatment **is likely linked to organic compounds** from soybean residues, but further chemical identification is needed
- Early **limitation of dissolved oxygen** can impair root respiration and nutrient uptake, but **may not fully explain the persistent growth inhibition**
- A second control - ½ Hoagland solution modified to match the N-NO_3:N-NH_4 of the waste mix treatment - is being analyzed to **rule out NH_4 toxicity** as a confounding factor

Outlook

- Further **chemical and biological characterization of the organic compounds** in soybean (and other plants envisaged to be grown in space) residues to **identify specific phytotoxins**

- In previous studies from NASA*, the **pre-treatment** of plant residue extracts with **mixed microbial communities** or **oyster mushrooms** (*Pleurotus ostreatus*) prior to their supply to hydroponically grown plants showed promising results for plant growth, suggesting that **phytotoxic organic compounds can potentially be removed**

- In the MELiSSA loop, it is essential to **ensure that compartments I and II are capable of removing phytotoxic organic compounds** before nutrient solutions reach the higher plant compartment (CIVb)

* Garland and Mackowiak, 1990; Mackowiak, et al., 1996

Thank you for your attention

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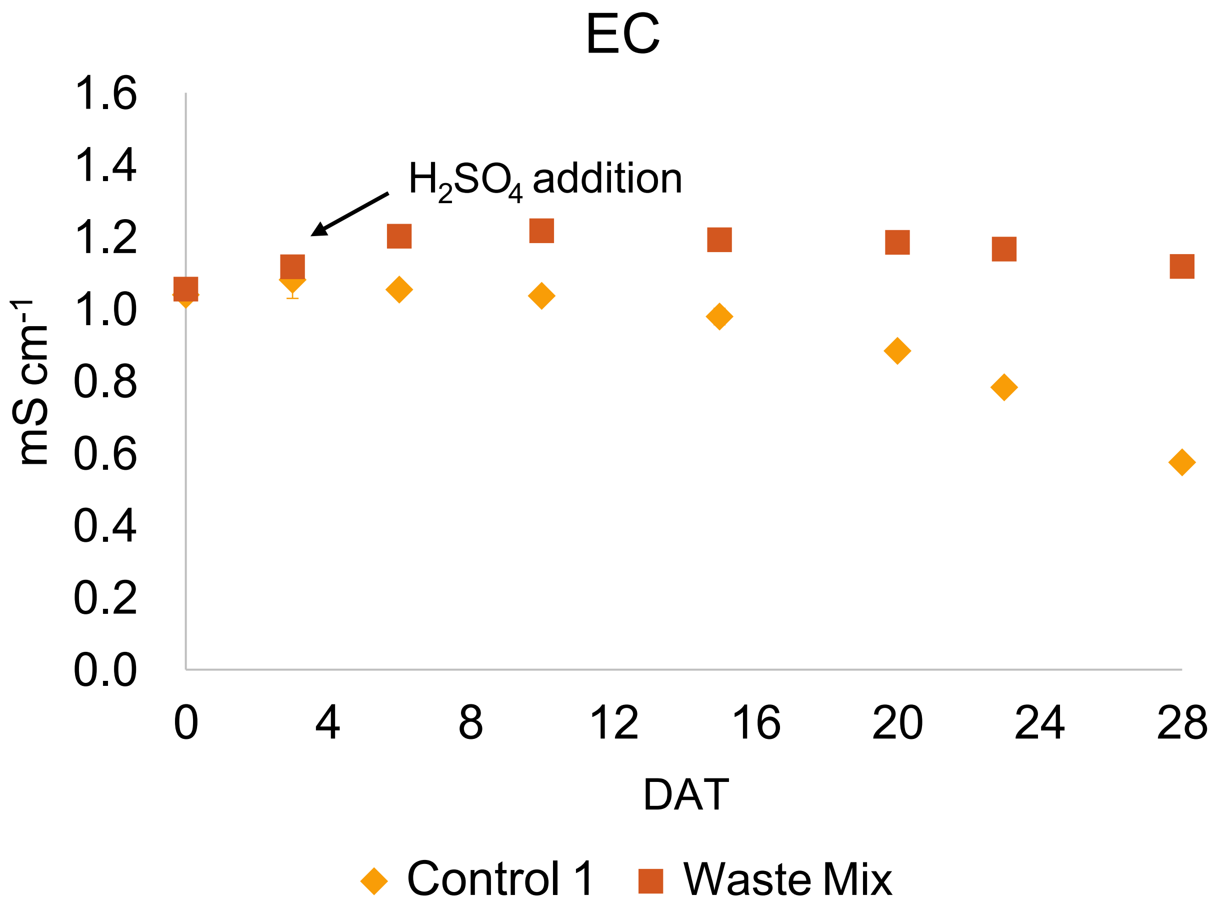
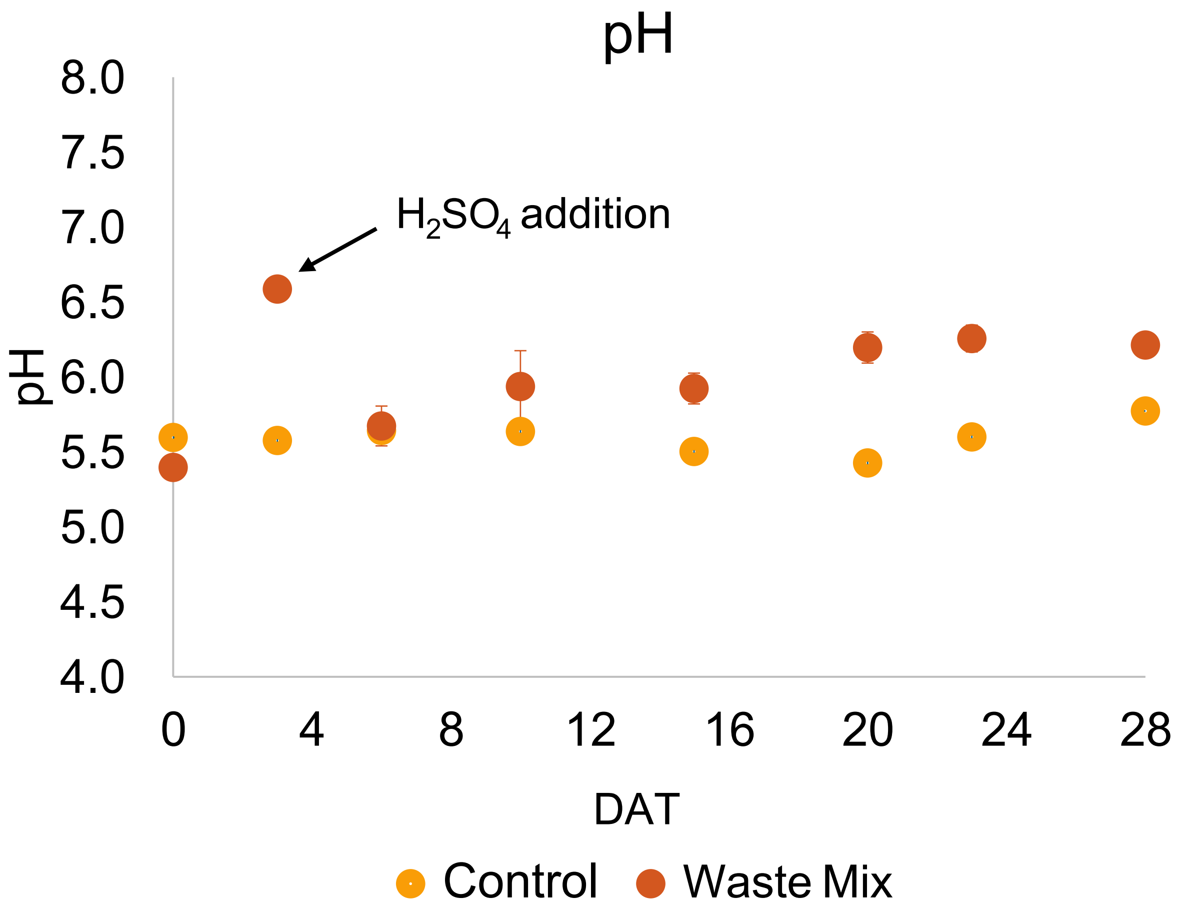
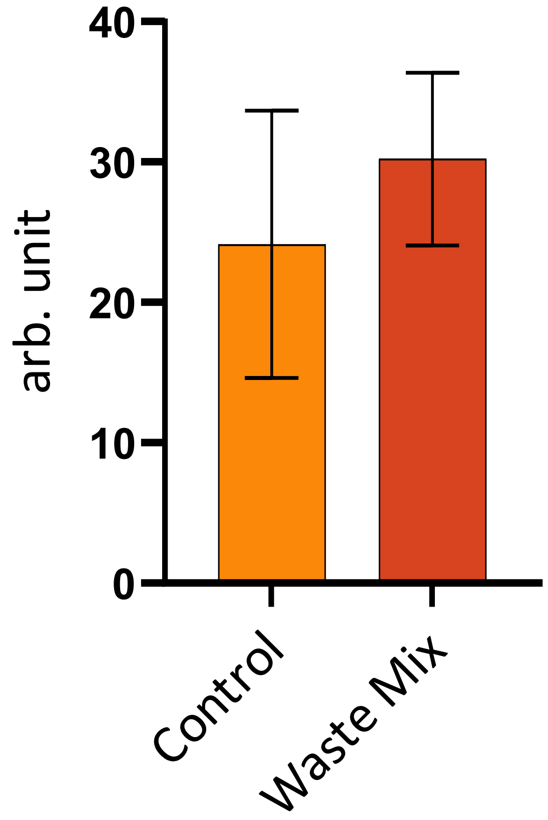
Results: pH and EC in nutrient solutions over time





Results: Lettuces grown in waste mix do not exhibit developmental abnormalities

Clorophyll content (SPAD)



SPAD and leaf number suggest an adaptive response to stress rather than developmental failure

Leaf number