



Modern Interpretations of the Three Sisters

Sustainable Polyculture for Urban Northern Climates

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Modern Interpretations of the Three Sisters: Sustainable Polyculture for Urban Northern Climates

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Abstract

This thesis explores the adaptation of the traditional Indigenous Three Sisters intercropping system (maize, beans, and squash) to modern, sustainable, and space-efficient growing formats in a northern urban context. Through a series of qualitative and semi-quantitative trials conducted in southern Sweden, four growing systems were tested: intercropped greenhouse bathtubs, outdoor intercropped raised beds, outdoor intercropped container pots, and outdoor monoculture beds, which served as a control for comparison. The study aimed to evaluate each system's performance in terms of plant health, weed suppression, pest resilience, growth efficiency, ecological cooperation, and space requirements. It also investigated the potential of substituting traditional crops with alternatives such as sunflower, zucchini, and cucumber. Results showed that the greenhouse bathtub system demonstrated the most vigorous growth and strongest interplant cooperation, while the container and raised bed systems showed promising potential with some limitations. Monoculture beds consistently underperformed across all criteria. Findings confirm that even under low-input conditions, the Three Sisters model, when adapted to contained formats, can support resilient, efficient, and ecologically beneficial food production in small spaces. The study highlights the potential of Indigenous-inspired polycultures for sustainable urban agriculture in northern climates and suggests pathways for further adaptation, biodiversity integration, and system optimization.

Keywords: Indigenous intercropping systems, sustainable urban farming, regenerative agriculture, cold-climate food production, agrobiodiversity

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1. Introduction

Traditional Indigenous agricultural systems such as the Three Sisters, an intercropping method combining maize, beans, and squash, represent centuries of sustainable land stewardship and ecological balance (Fonteyne et al. 2023; Kapayou et al. 2023). These systems not only provide nutritional complementarity and ecological benefits, but also reflect deep-rooted cultural knowledge and spiritual relationships with the land (Ba et al. 2018; Hayden & Hayden 2025). With increasing attention on sustainable food systems and climate-resilient agriculture, polyculture and intercropping systems like the Three Sisters model has re-emerged as a promising reference for agroecological design, particularly in small-scale and urban settings (Malapane et al. 2024; Cryan et al. 2025).

Although the Three Sisters originated in various Indigenous cultures of North and Central America, including the Haudenosaunee (Iroquois) in the northeast and the Maya and Aztec civilizations in Mesoamerica, the system's value extends beyond its original geographic and cultural contexts. It has been studied for its ability to suppress weeds, reduce pest pressure, and improve soil structure and fertility through the nitrogen-fixing ability of legumes such as beans (Kapayou et al. 2023; Enosh et al. 2025). In traditional field settings, these benefits are achieved through spatial arrangement and plant cooperation rather than external inputs like synthetic fertilizers or herbicides (Singh et al. 2020; Wang et al. 2022b).

The recent need to explore resilient and scalable food production systems has driven a renewed interest in applying traditional models like the Three Sisters to contemporary challenges. In particular, there is growing interest in adapting these systems for small-space gardening, urban agriculture, and alternative environments such as greenhouses or containers (Ju et al. 2021; Onwubiko 2022). While container gardening is commonly practiced in urban and peri-urban areas, little research has been done on how traditional intercropping systems perform in contained soil environments such as raised beds, reused bathtubs, large containers, or greenhouse-controlled spaces.

Given these documented ecological advantages, there is a compelling need to test whether the functional roles of the Three Sisters system can be replicated in non-traditional growing environments, particularly those aligned with modern sustainable gardening practices. This thesis explores the feasibility of adapting the traditional Three Sisters intercropping system, along with alternative combinations such as sunflower, cucumber, and zucchini, to container- and raised-bed formats adapted to peri-urban growing conditions in southern Sweden. The goal is to assess whether simplified, sustainable, and space-efficient

interpretations of this Indigenous polyculture can offer comparable ecological and agronomic benefits under both controlled and local outdoor conditions.

Four experimental groups were established to evaluate the performance of the Three Sisters system and its adaptations under different growing conditions. The first group was cultivated in bathtub containers inside a greenhouse, simulating the warmer, more irrigated conditions associated with traditional Mesoamerican agriculture, but adapted to a modern, resource-efficient context. The second group was grown outdoors in raised beds using intercropping methods inspired by the Iroquois version of the Three Sisters, tailored for urban and peri-urban farming settings. The third group involved large plastic containers arranged outdoors and planted with intercropped combinations, representing compact setups such as balconies or courtyards. The fourth group, also outdoors in raised beds, consisted of monocultures of each species grown separately, serving as a comparative reference to evaluate the benefits and limitations of intercropping.

It was hypothesized that intercropped systems, particularly those in the protected greenhouse environment, would outperform monocultures in terms of plant health, weed suppression, and moisture retention. These benefits were expected to arise from plant cooperation, spatial efficiency, and natural nitrogen cycling, especially in low-input growing conditions.

A mixed qualitative and semi-quantitative approach was employed to capture system performance, including visual plant health assessments, soil measurements, and photographic documentation. By observing factors such as plant health, weed suppression, pest occurrence, growth vigor, and visible nitrogen-related effects, this study aims to evaluate the practical potential and ecological value of container-based and raised-bed Three Sisters adaptations. The findings contribute to a broader understanding of how Indigenous agricultural systems can inform sustainable, low-input food production in both rural and urban settings.

1.1 Research Questions

This thesis is guided by the following research questions:

1. How well can the Three Sisters intercropping system be adapted to northern climates using modern, sustainable, and contained formats such as bathtubs, containers, and raised beds in both greenhouse and outdoor environments?
2. How do the different systems compare in terms of plant health, weed suppression, pest resilience, growth performance, and space efficiency in a Swedish peri-urban context?

3. What are the functional and ecological outcomes of Three Sisters-style intercropping compared to monoculture, particularly regarding interplant cooperation, visual indicators of nitrogen facilitation, and overall resilience under low-input conditions?
4. Can crops like sunflower, cucumber, or zucchini effectively replace maize and winter squash in the Three Sisters model while maintaining its core ecological functions (support, nitrogen fixation, and ground cover)?

2. Literature Review

2.1 Origins and Cultural Significance of the Three Sisters

The Three Sisters is a traditional Indigenous intercropping system that combines maize (*Zea mays* L.), beans (*Phaseolus* spp.), and squash (*Cucurbita* spp.) in a symbiotic planting arrangement. This system was practiced across diverse Indigenous cultures in North and Central America for centuries before European colonization, serving not only as a method of food production but also as a culturally and spiritually grounded agricultural system (Fonteyne et al. 2023; Hayden & Hayden 2025).

Among the Haudenosaunee (Iroquois) and other Northeastern tribes of North America, the Three Sisters were personified as sacred beings whose cooperation mirrored the interdependence necessary for community well-being and environmental balance (Kapayou et al. 2023). The practice involved planting maize first as a central support structure, followed by beans that climbed the maize stalks and added nitrogen to the soil, and finally squash, which spread across the ground to suppress weeds and conserve moisture. This system reflects not only practical agronomic wisdom but also a worldview rooted in reciprocity, relationality, and respect for land (Ba et al. 2018; Stanly et al. 2024).

Among the Zuni people of the U.S. Southwest, the Three Sisters were also adapted into unique agroecosystems suited for arid environments. Maize formed the foundational crop, often planted in sunken waffle gardens or near runoff collection areas to maximize water use efficiency. Beans and squash were intercropped similarly, but the Zuni also emphasized spatial arrangements that maximized nutrient retention in challenging desert conditions (Muenchrath et al. 2023).

In Mesoamerica, similar polyculture systems were developed by the Maya and other Indigenous civilizations, often as part of the larger milpa system. These systems featured not only maize, beans, and squash, but also complementary crops like chili peppers and tomatoes, cultivated in rotational patterns that maintained soil fertility over long time scales (Fonteyne et al. 2023). The Aztecs also developed sophisticated methods such as chinampas, raised field beds in shallow lakes, that integrated the Three Sisters concept in irrigated and highly productive forms.

Beyond food production, the Three Sisters served as a cultural anchor for seasonal ceremonies, oral traditions, and intergenerational knowledge transfer (Hayden &

Hayden 2025). The crops were nutritionally complementary, with maize providing carbohydrates and support, beans offering protein and nitrogen fixation, and squash supplying essential vitamins and ground cover. This integration of nutritional, ecological, and cultural values has led many scholars to recognize the Three Sisters as an example of Indigenous agroecology, a field that bridges ecological function with cultural identity and sustainability (Kapayou et al. 2023; Stanly et al. 2024).

Today, reviving the Three Sisters is not only an agronomic interest but also a political and ethical act, as Indigenous communities and allied researchers seek to restore traditional knowledge systems as part of broader efforts toward food sovereignty, cultural resurgence, and ecological resilience (Kapayou et al. 2023; Hayden & Hayden 2025).

2.2 Agronomic Benefits of Intercropping

Intercropping, the practice of growing two or more crop species in proximity, is widely recognized for its potential to increase agricultural efficiency and ecological resilience. The Three Sisters system is a traditional form of intercropping that demonstrates many of these benefits, including improved productivity, weed suppression, pest regulation, and enhanced soil fertility.

2.2.1 Productivity and Land Use Efficiency

One of the primary advantages of intercropping is improved land equivalent ratio (LER), which measures the productivity of intercropped systems relative to monocultures. Several studies, including Cryan et al. (2025), show that maize, beans, and squash intercropped together can achieve higher total yields compared to when each crop is grown separately. These gains are often attributed to complementary use of space, light, and nutrients by the different species. For example, beans utilize vertical space by climbing maize stalks, while squash spreads horizontally across the soil surface, minimizing competition.

2.2.2 Weed Suppression

Weed suppression is another key benefit of intercropping systems. Squash, with its broad leaves and ground-covering growth habit, reduces sunlight reaching the soil, thereby inhibiting weed germination. In intercropping trials, Enosh et al. (2025) found that maize-based intercropping systems showed significantly lower weed density and required fewer interventions compared to monoculture systems managed without herbicides. This effect is particularly important in sustainable and organic systems where chemical weed control is avoided.

2.2.3 Pest Regulation

Intercropping can also lead to reduced pest pressure, as crop diversity disrupts the spread and concentration of pest populations. Polycultures are less attractive to pests that specialize in a single crop and may also support beneficial insects that contribute to pest control. In a study on urban vegetable intercropping systems, Ju et al. (2021) reported healthier plant growth and lower incidence of pests in intercropped plots, especially those containing legumes.

2.2.4 Soil Fertility and Microbiology

Soil fertility enhancement is most evident in intercropping systems that include legumes such as beans, which fix atmospheric nitrogen through their symbiotic relationship with rhizobia bacteria. This process, known as Biological Nitrogen Fixation (BNF), as seen in Figure 1 below, involves the enzymatic conversion of atmospheric nitrogen gas (N_2) into ammonia (NH_3) within specialized root nodules. These nodules are formed primarily on the taproots of legumes, where rhizobia colonize and carry out nitrogen fixation using the nitrogenase enzyme complex under low-oxygen conditions. Although ammonia is the immediate product of this process, it is not absorbed directly by plants in its gaseous form. Instead, the NH_3 is quickly converted into ammonium ions (NH_4^+) within the plant's root tissues, which are readily taken up and used to synthesize essential amino acids, nucleotides, and chlorophyll precursors (Baber et al. 2018; Michel et al. 2020). The activity of rhizobia not only benefits the host legume but also enriches the surrounding soil with nitrogen compounds that can support neighboring crops in intercropping systems. After the growing season, when legume roots and plant matter decompose, the fixed nitrogen is further released into the soil, enhancing fertility for subsequent plantings even in the following year (Michel et al. 2020). Wang et al. (2022b) showed that nitrogen trade-offs between maize and legumes in long-term intercropping systems significantly improved maize productivity without external nitrogen inputs. Similarly, Singh et al. (2020) demonstrated that intercropping soybeans with cereals improved energy use efficiency, nutrient cycling, and overall profitability in rain-fed conditions.

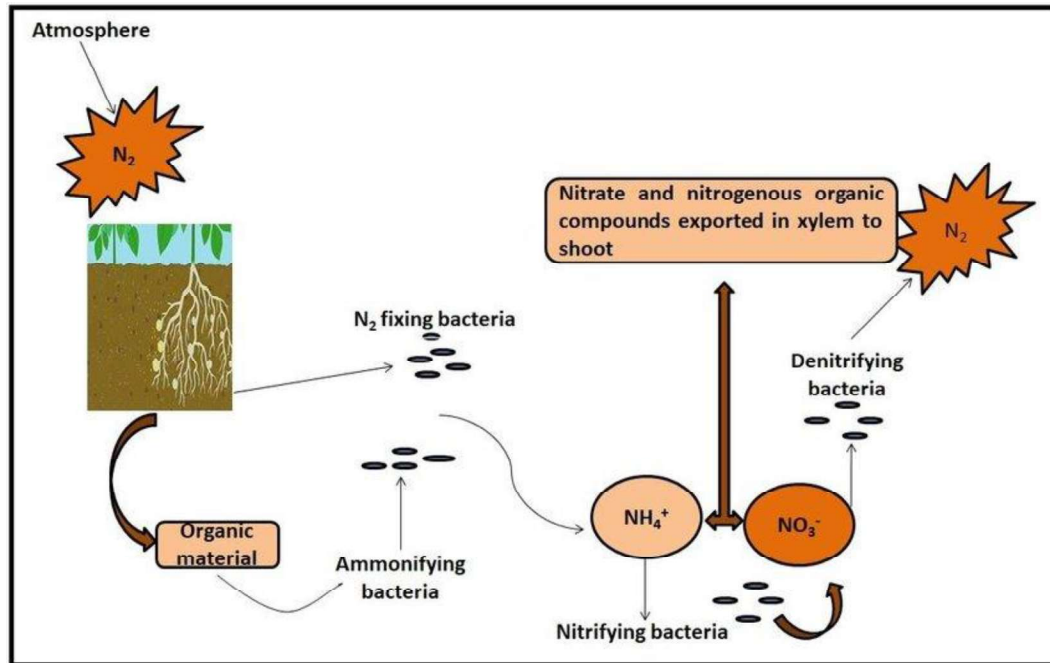


Figure 1. Biological nitrogen fixation (Baber et al. 2018)

2.2.5 Water Use and Stress Resilience

Beyond these direct agronomic benefits, intercropping systems also show greater resilience to environmental stress, including water scarcity. Research by Wang et al. (2022a) on maize-soybean and soybean-wheat intercropping indicated more efficient water use due to differentiated root architectures and phenological stages. These findings suggest that intercropping may buffer crops against variable weather conditions and contribute to long-term sustainability. Zhang et al. (2025) further emphasizes that maize intercropping systems not only enhance productivity but also improve farmland ecosystem services such as nutrient cycling, carbon sequestration, and pest regulation, aligning closely with the ecological goals of polyculture systems like the Three Sisters.

Taken together, the evidence supports the conclusion that traditional intercropping systems like the Three Sisters are not only culturally significant but also agronomically beneficial. Their integration of spatial, temporal, and functional diversity enhances ecosystem services and offers a viable model for sustainable agriculture in diverse settings.

2.3 Modern Applications of Traditional Systems

As global food systems face increasing challenges from climate change, land degradation, and urbanization, there is renewed interest in adapting traditional agricultural practices to modern sustainability goals. Indigenous systems such as the Three Sisters offer a model of polyculture that integrates biodiversity, soil

conservation, and ecological balance. Contemporary researchers and communities are exploring ways to apply these principles in new contexts, including small-scale, urban, and resource-constrained environments.

In recent years, there has been a growing recognition of the value of Indigenous agricultural knowledge in shaping resilient and equitable food systems. Hayden & Hayden (2025) proposes a framework for participatory research that centers Indigenous voices and cultural priorities in agricultural science. This shift from extractive to collaborative approaches aligns with broader efforts toward food sovereignty and environmental justice, where practices like the Three Sisters are not only agronomic tools but also expressions of cultural identity and resistance to colonial systems.

One key area of modern adaptation is the integration of Three Sisters principles into urban and small-space agriculture. For example, Fonteyne et al. (2023) reviews efforts to adapt the milpa system, a broader Mesoamerican form of intercropping that includes maize, beans, squash, and other crops, into settings where traditional land access is limited. These adaptations often require modifications in spacing, crop selection, and timing but preserve the foundational principles of mutual support, nutrient sharing, and biodiversity.

Community-led programs are also reintroducing and teaching Three Sisters gardening as a way to promote food security and cultural reconnection. Kapayou et al. (2023) documents a collaborative project between Native growers and scientists that integrates soil health monitoring with Indigenous land practices. The project demonstrates how traditional intercropping can regenerate soil organic matter, support pollinator populations, and create meaningful community engagement.

In Southern Africa, similar strategies are used by the Vhavenda people, who practice multi-crop planting in home gardens as a form of ecological resilience and cultural continuity. Malapane et al. (2024) emphasizes that these practices are not remnants of the past but active, adaptive systems that respond to environmental and social realities. Likewise, Stanly et al. (2024) argues for a deeper integration of Indigenous agroecology into global sustainability frameworks, noting that traditional knowledge systems offer solutions not only for productivity but also for ethical and relational approaches to land.

These modern applications of traditional intercropping systems are especially relevant in urban farming and climate adaptation contexts. They demonstrate that the underlying logic of the Three Sisters (cooperation, diversity, and resource efficiency) can inform innovative solutions for food production, even in non-traditional settings such as greenhouses or repurposed containers. By recognizing

the contemporary relevance of Indigenous systems, researchers and practitioners can bridge the gap between ancestral knowledge and future agricultural innovation.

2.4 Container-Based Growing Systems and Small-Space Agriculture

As urbanization increases and access to arable land decreases, container-based agriculture has emerged as a practical and adaptable solution for growing food in limited spaces. From backyard gardens to rooftop systems and balcony planters, containers offer flexibility in environments where in-ground cultivation is not feasible. Despite their widespread use, limited research has examined how traditional polyculture systems such as the Three Sisters perform in container settings like raised beds or repurposed household objects such as bathtubs.

Container gardening allows for soil control, modular arrangement, and easier management of inputs like water and compost. Onwubiko (2022) emphasizes that container cropping improves access to fresh produce in peri-urban and resource-constrained environments. Containers can be filled with carefully selected soil-compost mixtures, fitted with drainage systems, and arranged to optimize sunlight exposure. These features make them ideal for experimentation with intercropping in environments that mimic traditional systems in form but not in landscape scale.

In greenhouse or protected settings, container systems allow for season extension and climate simulation. This is particularly relevant for testing traditional systems like the Three Sisters in temperate climates where outdoor growing seasons may be too short or variable for full crop development. Ju et al. (2021) investigated intercropped vegetables in building-integrated greenhouses and found enhanced crop vigor and nutrient content, especially in systems including legumes. This supports the idea that even in constrained volumes, interspecies cooperation can lead to improved performance.

The use of bathtubs as growing containers is one example of low-cost, resource-conscious design. Though not widely studied in peer-reviewed literature, this approach aligns with broader urban agriculture principles of reuse and sustainable practice. Raised beds and confined growing spaces are becoming increasingly relevant in community gardens, school programs, and refugee integration projects, where the goal is to grow meaningful amounts of food using minimal land and infrastructure (Wang et al. 2023).

Cryan et al. (2025) explored intercropping systems in constrained field plots and suggested that even under space limitations, the benefits of spatial cooperation, especially when legumes are involved, remain evident. While most intercropping

studies focus on field-scale applications, findings from container-based systems show promise for adapting these methods to urban and suburban contexts. However, challenges such as root space competition, nutrient leaching, and microclimate fluctuations must be considered and managed carefully.

By exploring container-based versions of the Three Sisters, this thesis contributes to a growing body of research seeking to integrate traditional agricultural logic with modern sustainability needs. Such systems are not only practical in terms of land use efficiency, but also pedagogically valuable in demonstrating how ancestral practices can inform future food solutions.

2.5 Species Substitution in Polyculture Systems

While the traditional Three Sisters system is centered around the interdependence of maize, beans, and squash, modern adaptations increasingly explore the potential for substituting one or more of these species to suit local conditions, space constraints, or cultural preferences. Substitution may involve using alternative plants that fulfill similar structural, nutritional, or ecological roles within a polyculture, without compromising the intended functional relationships among species.

For example, in environments where maize is not suitable due to climate, space, or light limitations, crops like sunflower (*Helianthus annuus* L.) have been considered as an alternative vertical support. Sunflowers offer a tall, sturdy structure for climbing legumes, provide edible seeds, and attract pollinators and beneficial insects. Although limited literature directly investigates sunflower-bean intercropping as a substitute for maize, the conceptual framework is supported by broader studies on crop functional roles. Oyeogbe et al. (2021) demonstrated that substituting secondary crops in maize-based intercropping systems can still maintain productivity and ecosystem benefits, provided the replacement crop has similar growth habits and complementary timing.

Likewise, cucumber (*Cucumis sativus* L.) has been explored as an alternative to squash in small-space polycultures. Both crops are sprawling vines with ground-covering habits that suppress weeds and conserve soil moisture. Singh et al. (2020) analyzed different planting patterns of legume-based intercropping systems and noted that success depends less on species identity and more on role compatibility, resource use efficiency, and growth timing. This suggests that the core value of the Three Sisters lies not strictly in its species composition, but in the strategic use of functional diversity. Furthermore, Zhu et al. (2023) highlight how phosphorus availability influences plant–plant interactions in maize-legume intercropping, indicating that nutrient dynamics can significantly mediate both competition and cooperation in polyculture systems. Such findings underscore the

importance of matching substituted species not only by role but also by nutrient compatibility.

Trait plasticity is also a relevant factor in substitution studies. Yang et al. (2025) found that intercropping systems promote plastic responses in plant architecture and physiology, allowing crops to adapt to year-to-year variation and spatial constraints. This adaptability may allow alternative species to slot into traditional roles with minimal disruption to system performance. For example, sunflowers may not fix nitrogen but could still provide the vertical support and pollinator benefits that maize offers in the original design.

However, substitution does present challenges. Maize's C4 photosynthesis pathway, nitrogen-demanding nature, and dominance in intercropping dynamics are not easily replicated. Likewise, squash's dense leaf canopy and late-season growth pattern may be difficult to match exactly with cucumber or other alternatives. Any substitution must consider the entire system's phenological timing, nutrient needs, and space-sharing dynamics to avoid competition or imbalance.

In experimental and home-scale applications, substitutions like sunflower and cucumber offer a valuable opportunity to test the flexibility of traditional systems under modern conditions. These trials not only expand the potential of intercropping beyond historical boundaries but also reinforce the principle that sustainable agriculture is not about rigid replication, but about understanding and applying ecological relationships in diverse ways.

3. Materials and Methods

3.1 Research Design

This study employed a comparative, practice-based field design to assess the feasibility and ecological functionality of the traditional Three Sisters intercropping system (maize, beans, and squash) and its modern adaptations under varied growing conditions.

The research followed a qualitative-dominant, mixed-methods approach, incorporating visual and structural assessments of crop health, spatial interaction, and growth behavior, alongside basic quantitative estimates of spatial use and crop presence. The experimental layout was constructed to simulate real-world scenarios in urban and peri-urban horticulture and explore container-based alternatives to traditional open-field planting.

The rationale for this design was to evaluate both traditional and modified systems in formats that reflect increasing interest in sustainable, small-space, and self-reliant food production methods. As a single-observer, low-tech study, some subjectivity in visual assessments is acknowledged, particularly in evaluating plant vigor or pest damage.

3.2 Site and Setting

The fieldwork for this thesis was conducted in Skånes Fagerhult, a small locality in the northwestern part of Skåne region, in southern Sweden. The growing period spans from mid-May to early October 2025, with seed sowing taking place in mid-May, and the final observations recorded in early August. The site is located on private land used for horticultural experimentation and self-sufficient food production.

The area receives full sun for most of the day and is sheltered from prevailing winds by adjacent vegetation and fencing. The region has a temperate oceanic climate, with mild summers, moderate rainfall, and relatively long daylight hours during the peak growing season.

No traditional field or mound systems were used. Instead, all growing took place in containers or raised bed systems to reflect common limitations in urban and suburban food-growing contexts.

The growing environments included:

- Greenhouse bathtubs: Ten upcycled bathtubs (each approximately 1 m²) installed in two rows inside a greenhouse (total cultivation area ~10 m²).
- Outdoor intercropping beds: Raised beds (pallet-height frames placed directly on the ground) spanning approximately 10 linear meters.
- Outdoor container pots: Ten 50-liter plastic containers (~1 meter diameter), grouped into two rows of six and four, positioned among the outdoor beds to simulate balcony- or patio-style intercropping systems (total footprint ~10 meters).
- Outdoor monoculture beds: Three separate raised bed sections, each 5 meters long, used to grow maize, beans, and squash/cucumber independently (15 meters total).

All raised beds and containers were filled with soil-compost mixtures, and bathtubs were modified to allow drainage, mimicking the controlled irrigation and moisture-retention properties of traditional Mesoamerican chinampas and mound systems. No open-field or bare-soil cultivation was included in the study.

3.3 Crop Combinations and Treatments

Four primary cropping setups were implemented to assess the feasibility and ecological performance of Three Sisters-style intercropping under varied conditions: greenhouse bathtubs, outdoor raised intercropping beds, large outdoor container pots, and outdoor monoculture beds. Each setup allowed for comparisons across planting methods, spatial arrangements, and crop substitutions. The greenhouse bathtubs, with their enclosed format and ability to retain consistent subsoil moisture, share similarities with the chinampas developed by Indigenous communities in Mesoamerica which were moisture-stable planting beds used in high-water environments to support intensive polyculture. At the same time, all four systems can be seen as modern parallels to the Zuni waffle bed technique, where bordered, compartmentalized growing areas were designed to conserve water and manage soil conditions in arid climates. Like the Zuni system, these plots emphasize spatial control, low-input sustainability, and ecological cooperation among crops.

The greenhouse bathtubs served as a partially controlled environment with higher temperatures and reduced exposure to wind or rainfall. These upcycled bathtubs were filled with a compost-rich soil mixture and arranged in two rows within the greenhouse space. Most tubs followed the traditional Three Sisters configuration, with maize acting as vertical support for climbing beans and squash serving as a living ground cover. In a subset of the tubs (1/3), crop substitutions were tested: sunflowers replaced maize in some cases, while cucumber substituted for squash

in others. Each bathtub typically contained four maize (or sunflower) plants, three squash (or cucumber) plants, and between four and six bean plants. These were spaced according to companion planting principles to encourage natural cooperation among the species. Vertical trellises were not used for climbing beans, as they were expected to grow up the maize or sunflower stalks; however, long squash vines were gently supported using vertical structures where needed, primarily to lift heavier fruits off the ground, prevent damage, and optimize space in the limited confines of the greenhouse where full ground sprawl was not feasible.

The outdoor intercropping beds, constructed as pallet-height raised beds directly on the soil surface, replicated the same crop combinations and ratios used in the greenhouse tubs. So around 40 maize, 30 squash, and 60 bean plants. These plots also included some crop substitutions (e.g., cucumber for squash), though the majority followed the traditional Three Sisters grouping. The beds covered approximately ten meters in total, with the same proportional plant counts used in the bathtub configuration, scaled to the longer plot length.

The third setup, outdoor container pots, consisted of ten large 50-liter plastic containers, each representing a compact intercropping system suitable for balcony or courtyard environments. Initially germinated in the greenhouse, the containers were relocated outdoors in mid-May and clustered alongside the raised beds. Each pot was planted with 1-2 maize, 1-2 squash (one third used cucumber instead), and 2-3 climbing bean plants. This planting configuration mimicked the logic of the Three Sisters system on a micro scale, allowing for observation of plant cooperation and space usage in a containerized format.

To serve as a comparative reference or control group, outdoor monoculture beds were planted in a separate section of the garden. These consisted of three five-meter raised beds, each dedicated to a single species: maize (40), squash (30), beans (60). The total number of plants per species in the monoculture plots was matched to the quantities used in the intercropping plots, but more space was required overall due to the separation by crop type. This configuration allowed for an assessment of spatial efficiency, plant performance, and ecological trade-offs between monoculture and intercropping.

Together, these four systems provided a comparative framework to evaluate how the Three Sisters planting method, both in traditional and adapted forms, performs under varying spatial, environmental, and climatic conditions in a peri-urban Swedish context.

3.4 Materials and Growing Media

All planting media consisted of a homemade compost base, prepared over the prior year using primarily fresh grass clippings, leaf matter, and uncooked vegetable scraps. This mix reflects a nitrogen-rich green compost and food waste blend. No chemical fertilizers, pesticides, or commercial amendments were used. While the compost was not chemically analyzed, it was likely high in nitrogen and moderate to low in phosphorus and potassium. The compost was mixed with recycled soil from the previous season, and the ratio was kept approximately consistent across all treatments. Due to exposure to rainfall in outdoor settings, some nutrient leaching was expected during the season. Soil conditions were monitored using a simple handheld pH and moisture meter, where pH ranged from 3 to 10 (alkaline) and moisture from 0 to 10 (wettest).

Bathtubs and containers were equipped with bottom drainage to prevent waterlogging while retaining subsoil moisture. Squash vines in the greenhouse were trained upward to support developing fruits, but no formal trellises were used. No synthetic weed barriers or mulches were added, as one objective of the study was to test the system's natural efficacy in suppressing weeds through plant-based ground cover. This approach also aimed to keep the cultivation process as low-input and sustainable as possible, aligning with the principles of minimal intervention and ecological self-regulation.

3.5 Cultivation Conditions

All plots received approximately equal treatment regarding soil inputs, pest management (none), and fertilization (none). Watering was applied once per week in the greenhouse, depending on ambient temperatures. Outdoor plots relied primarily on rainfall and received supplemental watering only in cases of extended dry periods.

Greenhouse conditions offered more controlled moisture retention, partial evening shading, and protection from wind and heavy rain via clear plastic sheeting. Outdoor plots received full sun from late morning through evening. The ten container pots were placed outdoors among the raised beds, exposed to the same environmental conditions as the other outdoor systems.

Sowing was conducted via direct seeding in all treatments. To optimize growth potential in each setting, fast-growing, short-season, and compact plant varieties were selected, specifically adapted to the northern European climate and shorter growing window. Dwarf and bush-type cultivars were prioritized to accommodate limited space in containers and raised beds. Greenhouse crops were sown in early May, approximately two weeks earlier than outdoor plots, which were seeded

from mid to late May depending on weather conditions and soil readiness. Beans were introduced only after maize (or sunflower) reached approximately 10 cm in height, to minimize early competition and ensure adequate vertical support. Squash was planted concurrently with maize in all plots. In some outdoor beds, bird damage necessitated the re-sowing of squash shortly after germination. The selected crop varieties and their typical maturity timelines under Swedish growing conditions are outlined in the following table:

Table 1. Selected crop varieties, their maturity timelines , and location planted.

Crop	Days to maturity	Location planted
Maize (<i>Zea mays</i> , 'Damaun')	85-95	Used in bathtubs, intercropping and monoculture beds.
Maize (<i>Zea mays</i> , 'White Selection')	80-85	Used in containers. Shorter variety.
Pole beans (<i>Phaseolus vulgaris</i> , 'Blue Lake')	65-75	Used in throughout plots.
Pole beans (<i>Phaseolus vulgaris</i> , 'Blauhilde')	65-75	Used in throughout plots.
Winter squash (<i>Cucurbita maxima</i> , 'Uchiki Kuri')	85-95	Used in bathtubs, intercropping and monoculture beds.
Zucchini (<i>Cucurbita pepo</i> , 'Black Beauty')	45-60	Used in containers. Smaller bush plant.
Sunflower (<i>Helianthus annuus</i> , early-bloom types)	60-80	Substituted for maize in 1/3 of the bathtubs.
Cucumber (<i>Cucumis sativus</i> , 'Marketmore')	60-70	Substituted for squash in 1/3 of the containers and bathtubs.

3.6 Ethical and Practical Considerations

As the experiment did not involve human participants, ethical approval was not required. No genetically modified organisms or restricted species were used. All practices followed pesticide-free and sustainable gardening principles to reflect realistic home-based food production methods. All data collected was either visual, photographic, or based on manual records by the researcher, with no automated or sensor-based measurement systems used.

This project draws inspiration from Indigenous agricultural knowledge systems, specifically the Haudenosaunee and Mesoamerican traditions. While no direct collaboration with Indigenous communities occurred, their contributions are acknowledged with respect, and efforts were made to represent these systems accurately and ethically through scholarly sources.

3.6.1 Alignment with the UN Sustainable Development Goals

This research supports multiple United Nations Sustainable Development Goals (United Nations 2015) by demonstrating how traditional intercropping systems can be adapted for sustainable food production in compact, urban environments. It contributes to SDG 2 (Zero Hunger) by showing how nutrient-rich food can be grown efficiently in small spaces using low-input methods, increasing food self-reliance for households and communities.

By situating the study in a peri-urban Swedish context and using containers, raised beds, and recycled materials like bathtubs, the work aligns with SDG 11 (Sustainable Cities and Communities), offering practical strategies for integrating food production into city life. The use of homemade compost, pesticide-free methods, and minimal resource inputs further supports SDG 12 (Responsible Consumption and Production), promoting circular practices and reduced environmental impact.

In terms of climate resilience, the project contributes to SDG 13 (Climate Action) by encouraging local food systems that lower emissions associated with transport and chemical use, while also enhancing adaptability through polyculture. Finally, by fostering biodiversity, supporting soil health, and exploring plant cooperation, the research advances SDG 15 (Life on Land), reinforcing the role of regenerative gardening in sustainable land stewardship.

3.7 Data Collection

Data collection for this study was conducted throughout the 2025 growing season using a combination of structured visual observations, photographic documentation, plant measurements, and simple instrumental assessments. The aim was to capture both qualitative and semi-quantitative data related to plant performance, environmental responses, and ecological interactions across all four treatment groups: greenhouse bathtubs, outdoor intercropping beds, outdoor container pots, and outdoor monoculture beds. Weekly and biweekly assessments were used to ensure consistent tracking of system behavior over time.

Crop growth, development, and vegetative biomass were documented through regular visual inspections and direct measurements. Plant height was recorded using a measuring tape for maize, sunflower, and climbing beans, while vine length and overall canopy spread were noted for squash and cucumber plants. Climbing progress of beans and coverage behavior of trailing plants were recorded biweekly, providing a structured overview of growth dynamics. Additional notes were made on leaf density, color, and stem robustness to estimate relative vegetative biomass between treatments.

Yield potential was estimated based on observable indicators of reproductive development, such as the formation of corn ears, squash fruits, bean pods, and cucumber or sunflower heads. While full harvest data was not yet available by the end of the observation period, mid-season fruit set was tracked in all plots. The number of visible fruits per plant was recorded where possible, and photographic documentation supported comparisons across treatments.

Soil health was assessed using visual criteria alongside instrumental measurements. A handheld digital soil meter was used weekly to record pH and moisture levels in each bathtub, raised bed, and outdoor container. These readings were noted for each growing system and classified into standard horticultural categories. Soil texture, compaction, and visual quality were also assessed during manual weeding and watering activities, providing contextual insights into the growing media condition.

Weed pressure and pest presence were monitored through systematic visual inspection. Weed suppression was evaluated by estimating the proportion of exposed soil in each plot or container that was covered by unwanted vegetation. Manual weeding frequency and effort were recorded, allowing assessment of how effectively squash and cucumber plants functioned as living mulch. Pest presence was assessed by noting visual signs such as insect feeding damage, snail and slug trails, leaf holes, and white moth eggs. An ordinal scale (0 to 4) was used to estimate severity of damage, and trends were tracked over time, especially following rainfall or watering events.

Moisture retention was indirectly assessed by observing plant turgor, watering frequency, and soil surface conditions across different systems. While the greenhouse bathtubs and containers had partial protection from weather, outdoor plots were fully exposed to natural rainfall. Differences in drought stress or signs of moisture imbalance were noted in field journals and linked to soil meter readings where available.

Interplant synergy, competition, or failure was evaluated through visual comparisons of plant vigor and interaction within each intercropped system. For example, the presence of climbing beans in proximity to maize or sunflower was observed to support vertical growth, while enhanced leaf color and fewer signs of nutrient stress in those support crops suggested potential nitrogen benefits. Conversely, any evidence of competition (such as stunted beans in overly shaded areas or suppression from more dominant crops) was noted. Planting density and spacing were recorded for each treatment to support interpretation of these interactions in relation to performance.

Photographic documentation was a critical complement to field notes. Time-stamped images were taken regularly to capture key developmental milestones, monitor pest and weed dynamics, and confirm physical differences between systems. These images will be referenced throughout the results section and compiled in the appendix to provide transparent visual support for the study's findings.

3.8 Data Analysis

The data analysis for this study was primarily qualitative and descriptive in nature, suitable for the exploratory, small-scale, and observational format of the research. Nonetheless, a structured approach was applied to ensure that findings were systematically interpreted across the six defined key performance indicators: crop growth and development, yield potential, soil health, weed pressure and pest presence, moisture retention, and interplant synergy or competition.

Crop growth and development were analyzed using measurements of plant height, vine length, and canopy coverage, supplemented by visual indicators such as leaf size, density, and vigor. These observations were compared across the four growing systems: greenhouse bathtubs, outdoor intercropping beds, outdoor container pots, and outdoor monoculture beds. Growth stages were aligned with known maturity timelines for the selected crop varieties to assess whether each system supported timely development.

Yield potential was assessed through visual estimates of mid-season fruit set and flowering across the crop types. Where fruits or pods had developed, approximate counts were noted per plant or per container. While no final harvest data was available at the time of writing, these observations were used to estimate relative productivity across systems. Yield indicators were interpreted in conjunction with space use and crop density to assess spatial efficiency and potential productivity per square meter.

Soil health and moisture retention were evaluated using a combination of instrumental readings and field observations. Soil pH and moisture levels were measured regularly throughout the growing season using a handheld soil meter, and average values were calculated for each treatment group. These data helped assess whether different growing systems influenced substrate conditions. Moisture retention was further analyzed by integrating these readings with visual indicators such as plant turgidity, wilting, and watering frequency. Systems showing consistently healthy foliage with less frequent irrigation were considered more efficient at regulating moisture. Observations of soil texture, aeration, and organic matter content during manual tasks like weeding were also considered, allowing a more holistic interpretation of soil condition across treatments.

Weed pressure and pest presence were analyzed using ordinal scales. Weed coverage was estimated weekly and recorded as a percentage of ground exposure, allowing for trend comparisons between intercropped and monoculture systems. Pest damage severity was rated on a scale from 0 (no damage) to 4 (severe damage), and the frequency of pest sightings was tracked by system. By comparing weed and pest outcomes across systems, insights were drawn about the effectiveness of squash and cucumber ground cover, the role of plant diversity in pest deterrence, and the general resilience of each configuration.

Interplant synergy, competition, or failure was evaluated through visual observation of plant interactions within intercropped systems. Key indicators included the degree of climbing success in beans, shading impacts of squash on neighboring plants, and any visible evidence of growth suppression or mutual support. In particular, nitrogen-related effects were inferred by comparing leaf color and vigor of maize or sunflower growing near beans versus those in monoculture plots. These functional interactions were used to assess how well each adaptation preserved the core ecological roles of the Three Sisters model: support, nitrogen fixation, and ground cover.

Descriptive statistics (means, ranges, and relative proportions) were calculated where appropriate, particularly for plant height and fruit presence. No advanced statistical testing was performed due to the small sample sizes, the self-explanatory nature of the observational scales, and the exploratory purpose of the project. However, the triangulation of measurement data, visual observations, photographic evidence, and layout records supported robust pattern recognition across treatment groups. All data were compiled and analyzed manually using structured tables and visual annotation in Microsoft Excel and Word.

This mixed-method analysis enabled a grounded evaluation of each system's performance while respecting the practical limits of an urban, self-managed research project. Despite the absence of controlled experimental replication or formal inferential statistics, the data interpretation approach was rigorous enough to support meaningful conclusions about the feasibility and adaptability of Three Sisters intercropping in peri-urban container-based contexts.

The following section presents the results obtained through this multi-method evaluation framework. Observations are structured around the key performance indicators defined in this Section and organized by system type, beginning with the greenhouse bathtub intercropping and concluding with monoculture comparisons.

4. Results

This section presents the observational and semi-quantitative findings collected during the 2025 growing season. Outcomes are reported across four distinct growing systems: greenhouse bathtubs, outdoor intercropping raised beds, outdoor container pots, and outdoor monoculture raised beds. The analysis includes plant height and development, soil conditions, pest resilience, weed suppression, and signs of nitrogen cooperation. All data reflect the seasonal performance of both traditional Three Sisters combinations and alternative plant pairings adapted for Swedish conditions.

Summary tables of key measurements are provided in the tables below, including Table 2, which presents average soil pH and moisture levels across the four treatment groups, and Table 3, which reports average plant height or vine length for maize, sunflower, squash, and beans in each growing system.

Table 2. Average soil pH and moisture levels by treatment group

Treatment Group	Average pH	Average Moisture
Greenhouse bathtubs	7.00	9.00
Outdoor raised intercropping beds	6.75	6.75
Outdoor container pots	6.50	8.50
Outdoor monoculture beds	6.50	5.00

Table 3. Average plant height or length (cm) by treatment group and crop

Treatment Group	Maize	Sunflower	Squash	Beans
Greenhouse Bathtubs	210	180	180	165
Outdoor Intercropping Beds	130	–	300	170
Outdoor Container Pots	110	–	75	100
Outdoor Monoculture Beds	120	–	175	110

Note: The outdoor containers were planted with bush-type squash (not vining) and a shorter, fast-maturing maize variety. These plant types were intentionally selected for compact growth and early harvest, which should be considered when interpreting height differences across treatment groups.

To provide a comparative overview of qualitative trends observed across the four growing systems (Table 4), a 0 to 3 ordinal scale was used to rate key indicators of plant and system performance. The scale was defined as follows: 0 = none or absent, 1 = low, 2 = moderate, and 3 = high. Five dimensions were evaluated based on visual assessments and observational field notes: leaf density (as an indicator of plant health and canopy coverage), pest presence (insect or animal activity), weed presence, visible plant cooperation (e.g. beans climbing maize,

squash ground cover), and overall plant growth. While these ratings are not derived from formal instrumentation or sampling, they give a structured interpretation of field performance trends across treatments.

Table 4. Comparative Observations of Plant Health, Interaction, and Pressure Factors

System	Leaf Density	Pest Prescence	Weed Prescence	Plant Cooperation	Plant Growth
Greenhouse Bathtubs	2	1	1	3	3
Outdoor Intercropping Beds	3	2	2	1	3
Outdoor Container Pots	1	1	1	2	2
Outdoor Monoculture Beds	2	3	3	0	1

4.1 Greenhouse Bathtubs

The greenhouse bathtub system demonstrated the most vigorous growth across all metrics (see Appendix 1, Figure 1 to 6). Corn reached an average height of 210 cm, with sunflower substitutions averaging 180 cm. Squash vines extended to around 180 cm, and beans climbed effectively, reaching 165 cm by early August. Beans paired with sunflowers climbed up to 150 cm (see Appendix 1, Figure 7 to 9). These plants developed rapidly, benefiting from earlier sowing, warmer ambient conditions, and high humidity in the enclosed environment.

Foliage appeared uniformly dark green and turgid, with very few signs of nutrient stress or chlorosis. The system showed minimal pest damage, though slugs and snails were occasionally found along the outer tubs and caused damage (see Appendix 1, Figure 20). Weed suppression improved over time; early-season hand weeding was necessary, but by late July, squash coverage had shaded nearly all exposed soil.

Average soil pH readings were approximately 7.00, and moisture levels averaged 9.00 on the meter scale, indicating moderately moist and neutral conditions ideal for vegetable growth. The presence of beans was associated with visibly healthier maize and sunflower foliage, suggesting effective interplant nitrogen cooperation.

4.2 Outdoor Intercropping Raised Beds

Raised beds planted with traditional Three Sisters and their alternatives performed moderately well, with more variability than the greenhouse group (see Appendix 1, Figure 10 to 12). Corn reached around 130 cm, squash vines up to 300 cm depending on the vine, and beans reached an average of 170 cm. Flowering occurred slightly later than in the greenhouse, but fruit and pod development was visible by early August.

Pest activity was more prominent in this setting. Slugs and snails were frequent following rainfall, and occasional bird damage required reseeding of squash in some areas. Nevertheless, most plants remained healthy and displayed signs of natural resilience. Maize growing near beans consistently showed deeper green foliage and fewer signs of stress than in the monoculture system.

Early-season weed coverage was high, but squash expansion improved suppression almost completely by July. Soil pH averaged 6.75, and moisture values also averaged 6.75, indicating neutral conditions and slightly moist soil. These conditions supported stable plant development, though slightly behind the greenhouse.

4.3 Outdoor Container Pots

The container group, consisting of ten large plastic pots with Three Sisters or substituted combinations, showed more limited growth overall (see Appendix 1, Figure 13 to 16). Some maize reached 110 cm, squash vines 75 cm, and beans also 100 cm. These plants were originally germinated indoors and moved outdoors in mid-May, which may have stressed their establishment.

While flowering was delayed and fruit set minimal by early August, some plants exhibited moderate resilience. Beans growing near maize still appeared to contribute positively to neighboring plant health, and foliage in these combinations was generally greener than monoculture controls. However, growth was clearly constrained by the limited root volume and fluctuating soil temperatures.

The container group had an average soil pH of 6.50 and moisture level of 8.50, which may have contributed to the healthy appearance of foliage but not to vigorous growth. Weed pressure was low due to the enclosed nature of the pots, and pest presence was moderate but manageable.

4.4 Outdoor Monoculture Raised Beds

The monoculture plots, consisting of three separate 5-meter beds for maize, beans, and squash, presented the most limited growth and highest exposure to pest and weed pressures (see Appendix 1, Figure 17 to 19). Corn reached 120 cm on average, squash up to 175 cm depending on the vine, and beans averaged 110 cm.

Foliage color was paler compared to intercropped counterparts, especially in the squash beds, where signs of chlorosis and leaf damage were common (see Appendix 1, Figure 21). Pest activity was higher than in other groups, with more

visible snail trails and droppings. Weed growth was substantial due to the lack of squash ground cover, requiring repeated manual weeding.

Average soil pH was 6.50, similar to the raised bed intercrop group, but average moisture levels were the lowest of all systems at 5.00. This may have contributed to the reduced vigor and increased signs of drought stress, especially during warmer weeks in June and July.

5. Discussion

5.1 Interpretation of Key Findings

The comparative analysis of the four cropping systems (greenhouse bathtubs, outdoor intercropping raised beds, outdoor container pots, and outdoor monoculture beds) showed clear differences in performance, resilience, and ecological function. Among all configurations, the greenhouse bathtubs demonstrated the most consistent and vigorous growth. This system combined favorable environmental conditions (stable warmth, higher humidity, and early planting) with deeper soil volumes and strong interplant cooperation. Corn reached nearly two meters, beans climbed effectively, and squash provided dense ground cover. These plants not only performed well individually but also fulfilled their intended ecological functions: the maize and sunflower provided vertical support, beans showed signs of nitrogen facilitation, and squash successfully suppressed weeds as living mulch. Furthermore, the use of discarded or secondhand bathtubs as growing containers added a highly sustainable dimension to this system, repurposing non-biodegradable waste into productive agricultural infrastructure. This approach minimized the need for new materials while maximizing durability and growing capacity, aligning with circular economy principles in sustainable horticulture.

Outdoor raised beds with intercropping also exhibited cooperative behavior between crops but with more variability and stress-related limitations. Growth was generally moderate, and weed suppression improved mid-season as the squash matured. However, the timing of seeding emerged as a critical factor; in many plots, beans struggled to overtake squash leaves and reach sunlight, particularly where corn was slow to establish. In one greenhouse bathtub with sunflower instead of maize, beans thrived more successfully, likely due to delayed squash growth allowing beans more time to ascend. This suggests that small shifts in crop timing or competition dynamics can significantly affect interplant synergy.

Container pots, while promising in design, showed the most restricted growth. However, these limitations appeared to stem more from environmental exposure and limited root volume than from the intercropping strategy itself. Despite their challenges, the containers performed reasonably well given their size and location, and results suggest that if relocated to a more controlled setting, such as a greenhouse, sunroom, or enclosed balcony, and paired with optimized crop varieties (e.g., compact squash or ultra-short corn), their outcomes might rival the bathtub system. This highlights the potential of container-based intercropping as a viable model for compact urban spaces. In particular, apartment dwellers with

access to balconies or large windows could benefit from this approach. A simple row of well-placed containers could yield nutritious food with minimal inputs, relying on the ecological cooperation of the Three Sisters to optimize space, suppress weeds, conserve moisture, support themselves vertically, and reduce the need for some external fertilizers. As such, this method represents a sustainable and space-efficient food production strategy for urban environments, requiring fewer resources while drawing on traditional agroecological principles.

In contrast, the monoculture beds demonstrated the weakest performance. Plants were more vulnerable to pests and weed pressure, and the absence of companion crops appeared to reduce nutrient cycling and structural protection. Corn in particular showed signs of stress, with paler foliage and signs of nitrogen deficiency, underscoring the role of beans in nutrient support. This difference in foliar health across systems aligns with traditional intercropping theory, where leguminous partners enhance system fertility and plant vigor.

The differences in plant performance between indoor and outdoor systems can be partly explained by the microclimates in each location. The greenhouse bathtubs received steady morning and midday sun and were protected from rain and wind. This created warmer and more humid conditions that helped the plants grow faster and stronger, especially in the early stages. The outdoor systems had more exposure to weather changes, such as cooler nights, rainfall, and some wind. These beds and containers got more sun in the afternoon and evening but were generally cooler and less stable overall. This may have slowed early growth, especially for crops like maize and squash that prefer warmth. However, the outdoor area was at least partly sheltered by surrounding structures or vegetation, so wind exposure was not extreme.

Another interesting pattern was seen in the soil pH levels between the different growing environments. The greenhouse bathtubs had the highest average pH at 7.00, while the outdoor raised beds measured 6.75, and both the outdoor containers and monoculture beds were slightly more acidic at 6.50. Since all systems were filled using the same batch of homemade compost and recycled soil, the starting nutrient availability and conditions were consistent. This suggests that there was sufficient soil fertility and microbial quality across treatments at the outset even if no direct measurements were taken. The observed pH differences are therefore likely a result of environmental exposure. Outdoor conditions such as rainfall and wind may have contributed to slight acidification, either through leaching of minerals or increased microbial breakdown of organic matter. These changes, although subtle, could have affected how nutrients were taken up by the plants and how well the soil microbes interacted with their root systems in each setting.

5.2 Intercropping Benefits vs. Monoculture

The results of this study reinforce the well-documented benefits of intercropping compared to monoculture systems. Across all intercropped plots (greenhouse bathtubs, raised beds, and container pots) plants exhibited stronger visual health, more stable moisture retention, reduced weed pressure, and greater resilience to pest damage than those in monoculture beds. By contrast, the outdoor monoculture plots showed the weakest overall performance, including paler foliage, more visible signs of nutrient stress (particularly in maize), and a higher frequency of pest damage and weed regrowth.

The synergistic relationships between the Three Sisters crops were most evident in the intercropped settings. Maize and sunflower functioned effectively as climbing supports for beans, particularly in the greenhouse bathtubs and outdoor raised beds. Where this support was successful, beans reached greater heights and contributed to visibly healthier surrounding foliage, suggesting active nitrogen fixation and improved nutrient availability. Squash played a critical role as a living mulch, eventually shading up to 95% of the soil in mature intercropped beds, thereby suppressing weed growth and reducing the need for manual weeding as the season progressed. This effect was especially pronounced in the greenhouse and raised bed systems.

In the monoculture beds, these benefits were noticeably absent. The maize plots in particular showed signs of chlorosis, likely due to the lack of nearby nitrogen-fixing beans, while exposed soil between plants encouraged weed growth despite repeated manual weeding. Pest damage was also more prevalent in monocultures, possibly because the uniform planting created a more predictable environment for herbivorous insects and slugs.

From an ecological standpoint, the intercropped systems not only supported healthier individual plants but also functioned more cohesively as mini-ecosystems. Moisture levels were more stable in intercropped plots, especially those with dense squash coverage, which likely reduced evaporation and temperature fluctuations at the soil surface. While formal yield data were not collected, the visual signs of vigor, early flowering, and pod or fruit development all suggest that the intercropped systems are more efficient under low-input conditions. This confirms previous findings in agroecological literature that intercropping can enhance resilience and sustainability while making better use of space and resources (Cryan et al. 2025; Enosh et al. 2025).

5.3 Adaptation to Northern and Peri-Urban Conditions

Adapting the Three Sisters intercropping system to Sweden's cooler, temperate climate and peri-urban conditions presented both challenges and promising outcomes. While the traditional system originates in the warmer and longer-season regions of the Americas, this study demonstrated that, with thoughtful planning and variety selection, the ecological functions and cooperative dynamics of the Three Sisters can be maintained even in a northern setting.

Success in this adaptation was strongly influenced by the growing format. The greenhouse bathtub system, with its protected environment, deeper soil, and earlier planting window, most closely approximated the original climate and conditions of the system's origin. The consistent warmth and stable humidity supported fast growth and interplant cooperation. This result highlights the greenhouse as a powerful tool for extending the growing season in northern latitudes, making Three Sisters-style systems viable even where summers are short.

The raised outdoor beds, while exposed to more variable weather and pest pressures, still supported effective intercropping. The squash plants took longer to mature but eventually offered excellent ground coverage, and the beans, once established, climbed well and contributed to nitrogen enrichment. However, both the beans and maize may have been sown too late in this group, resulting in early growth competition with squash vines. Earlier sowing of maize and beans in outdoor beds may improve interplant balance in future trials.

The container group reflected the realities of space-limited, urban or balcony gardening. While plants grew more slowly and remained smaller overall, the ecological model still functioned. This group showed that even modest setups can benefit from Indigenous-inspired polyculture. With modest improvements such as greenhouse placement, careful variety selection, or supplemental warmth, containers could support a robust and self-sustaining food production method in urban homes.

Altogether, the findings confirm that Three Sisters principles are adaptable to northern conditions with creative modification. Raised beds, greenhouses, and even containers offer formats that, while non-traditional, can still uphold the core benefits of this intercropping system, especially when supported by sustainable practices, such as compost-based soil and non-chemical cultivation.

5.4 Substitution of Crops

One of the central goals of this project was to explore whether alternative crops, specifically sunflower in place of maize and cucumber in place of squash, could successfully fulfill the functional roles in the Three Sisters model. The substitutions were selected based on practical considerations such as faster maturation, space efficiency, and adaptability to container or greenhouse cultivation in northern climates.

Sunflowers demonstrated notable promise as vertical support plants. While not as structurally rigid as maize, the taller specimens reached heights of 150 cm in the greenhouse bathtubs, providing a reliable climbing surface for beans. In fact, the most successful bean growth occurred in the sunflower group, likely due to delayed squash development in that particular tub, which allowed beans more time to establish without being overtaken by spreading vines. This suggests that sunflower can serve as a viable substitute for maize in systems where corn is difficult to grow due to space, season length, or variety limitations. However, it also indicates that the timing of interplant competition plays a critical role in the success of the substitution.

Cucumber, used in some containers and outdoor raised beds, yielded more mixed results. While cucumber vines did spread and begin to offer ground coverage, they lacked the dense, low-lying foliage of traditional squash varieties that is crucial for optimal weed suppression. Furthermore, cucumbers generally prefer more trellising or elevation, which was not provided in this system. Their fruiting and overall biomass were also lower than squash, likely due to either variety choice or slower establishment under the cool early-season conditions. Thus, while cucumber can offer some of the ground-cover benefits of squash, it may not be as reliable unless carefully managed or paired with more vigorous, short-season cultivars.

In contrast, zucchini was trialed as a bush-type alternative to winter squash in several plots. These compact plants performed very well in terms of ground coverage and showed good vigor without the need for any vine support. Their broad, low foliage suppressed weeds effectively, especially in systems where space was limited or vertical sprawl was undesirable. This makes zucchini a promising substitute for squash in northern or container-based Three Sisters setups where fast establishment and minimal support infrastructure are key.

Overall, the substitution trials highlight that flexibility is possible within the Three Sisters framework, but crop choice must be tightly aligned with both environmental conditions and planting design. Matching growth habits, maturation timelines, and structural needs is essential to maintaining the

ecological integrity of the system. Future substitution experiments should prioritize careful timing of sowing and selection of compact, cooperative plant types.

5.5 Limitations and Sources of Error

Despite the clear trends and patterns observed across the different growing systems, this study had several limitations that should be considered when interpreting its results. The most fundamental constraint was the reliance on primarily observational and semi-quantitative data. While plant heights, soil pH, and moisture were measured with basic tools, yield data were not fully quantified, and pest or weed impacts were assessed using ordinal scales and photographic evidence rather than standardized instruments. This limits the statistical generalizability of the findings but still provides valuable comparative insights.

Another important limitation was the variability in planting success. While effort was made to synchronize sowing times and crop combinations, some plots, particularly in outdoor settings, suffered from early bird and slug damage, which led to inconsistent germination. In response, some replacement planting was done using seedlings from a backup stock, but this introduced variability in plant age and establishment timing within certain beds or containers. As a result, growth comparisons may reflect not only system performance but also differences in individual plant start dates and resilience.

The performance of beans in particular was highly dependent on early development timing. In many plots, especially those where squash grew aggressively, the beans were shaded before they could climb effectively. This seemed to occur most in outdoor raised beds, where planting depth or timing may have been less than optimal. In contrast, in the sunflower bathtub, beans showed exceptional vertical growth, likely due to slower squash expansion in that bed. These interactions point to the importance of precise spacing and timing in mixed cropping systems. Factors that are challenging to perfect in a home-based field study but crucial for replicability.

Additionally, while containers performed acceptably, their exposed positioning outdoors likely limited their potential. Unlike the bathtubs in the greenhouse, the containers faced greater temperature fluctuation, wind stress, and rapid moisture loss. This environmental exposure, rather than the intercropping model itself, appears to have constrained their performance. Transplant stress may have also contributed, as these plants were moved outside after initial germination under sheltered conditions. Future experiments could improve upon this by preselecting ultra-compact varieties and maintaining consistent environments.

Another key limitation is that all trials were conducted at a single location: a garden in Skånes Fagerhult, in the northwestern part of the Skåne region of southern Sweden. While this provided a controlled context for comparing the four systems, it also means that the findings reflect the unique climatic, soil, and pest conditions of that particular region and season. Results may vary under different environmental conditions or in other parts of the country, and broader testing would be needed to confirm how well these system adaptations perform across varied northern climates.

Finally, the study's reliance on homemade compost and recycled soil, while sustainable and appropriate for the research goals, introduces another source of variability. Nutrient levels were not chemically analyzed, so subtle deficiencies or imbalances may have influenced plant vigor in ways not directly accounted for. However, this approach reflects real-world conditions in low-input urban gardening, making the findings highly relevant to those seeking practical and sustainable growing strategies.

5.6 Implications for Urban Farming and Indigenous-Inspired Models

The results of this study suggest that the Three Sisters intercropping method, when thoughtfully adapted, has strong potential for sustainable food production in urban and peri-urban environments. Each of the plant species fulfills a distinct ecological role (vertical support, nitrogen contribution, and living mulch) and when allowed to cooperate effectively, these functions can reduce the need for external inputs such as synthetic fertilizers, trellises, or plastic weed barriers. This makes the system especially appealing in contexts where space, time, and resources are limited. The modular nature of the system makes it highly scalable, from balcony pots to community gardens, offering adaptable food-growing strategies across different urban contexts. The Three Sisters themselves also offer a balanced nutritional profile, supporting household food security even in a compact and self-sufficient format.

The greenhouse bathtub system demonstrated how well-adapted intercropping can thrive in reused infrastructure. These bathtubs, originally waste materials, became productive growing spaces by combining depth, drainage, and containment. Their success reinforces the idea that urban agriculture does not require high-tech solutions; instead, it can rely on accessible materials, local knowledge, and ecological design. In particular, the reuse of containers aligns closely with the principles of circularity and low-impact growing that underpin many sustainability movements today.

Container-based systems also show promise for apartment dwellers or others without access to in-ground space. A simple row of well-placed containers on a balcony, sunroom, or rooftop could yield a surprising amount of fresh produce. When intercropped in the Three Sisters model, these setups offer space-efficiency, self-supporting crops, and minimal weeding or fertilization, making them both beginner-friendly and low-maintenance. Especially with early-maturing, compact crop varieties such as zucchini, and dwarf maize or sunflowers, the system can be customized to fit small footprints while retaining ecological function.

Beyond practical applications, this project also reflects on the wisdom embedded in Indigenous agricultural knowledge. The Three Sisters model originated from long-established systems used by Indigenous peoples across North America, whose agricultural practices were rooted in reciprocity, biodiversity, and sustainable land use. In this study, those same principles were applied to a modern Nordic climate using local materials and modified crop varieties. The resulting outcomes suggest that ancient models can be adapted without losing their core values and that modern sustainability movements have much to learn from Indigenous agricultural philosophies.

The Three Sisters system thus stands not only as a horticultural experiment but as a bridge between knowledge traditions. Its success in reused bathtubs and compact containers illustrates how resilient, cooperative growing methods can be revived and reimaged to meet the challenges of contemporary food systems, especially in urbanized, resource-constrained, or climate-affected regions.

5.7 Response to Research Questions

Research Question 1: *How well can the Three Sisters intercropping system be adapted to northern climates using modern, sustainable, and contained formats such as bathtubs, containers, and raised beds in both greenhouse and outdoor environments?*

The results of this study indicate that the Three Sisters system can be successfully adapted to northern climates when deployed in innovative and contained growing formats. The greenhouse bathtubs, in particular, demonstrated high adaptability and productivity under cool-temperate conditions. Their enclosed, stable environment, combined with deeper soil volume and repurposed materials, supported strong interplant cooperation and robust growth, despite the region's relatively short growing season. Outdoor raised beds also supported the system's viability, though more sensitive to timing and pest pressures. Even the container pots, while limited by root space and exposure, proved that this model can function in compact, urban spaces. Thus, when aligned with thoughtful planning, sustainable inputs, and climate-appropriate varieties, Three Sisters intercropping

can be effectively reimagined for northern, peri-urban settings in both indoor and outdoor formats.

Research Question 2: *How do the different systems compare in terms of plant health, weed suppression, pest resilience, growth performance, and space efficiency in a Swedish peri-urban context?*

The greenhouse bathtubs outperformed all other systems in plant vigor, pest resilience, weed control, and growth rates, thanks to their structure and function as deep, and self-contained growing vessels, in addition to the optimal environmental conditions of the greenhouse. Outdoor intercropping raised beds performed well overall but were more affected by environmental variability. Containers, while more limited in plant size, still showed respectable health and effective weed suppression, with the added benefit of extreme space efficiency suitable for balconies, courtyards, or rooftops. Monoculture beds lagged in every category, with visible nutrient stress, higher pest pressure, and insufficient weed control. Each monoculture type also introduced distinct challenges: maize plots experienced more rapid soil drying and signs of nitrogen deficiency; squash beds retained moisture better but suffered the most from pest activity, particularly slugs and insects targeting broad leaves; and beans, while less affected by pests, require climbing support and more human inputs to grow effectively in the absence of companion crops. Across all intercropped systems, the space-saving effect was clear: by combining vertical and horizontal plant functions (climbing beans, upright maize or sunflower, and sprawling squash) intercropping maximized use of limited land without sacrificing ecological function. This synergy supports the conclusion that intercropping not only yields the best overall ecological balance but also is more spatially efficient in urban and peri-urban agriculture.

Research Question 3: *What are the functional and ecological outcomes of Three Sisters-style intercropping compared to monoculture, particularly regarding interplant cooperation, visual indicators of nitrogen facilitation, and overall resilience under low-input conditions?*

Three Sisters-style intercropping consistently outperformed monocultures in functional and ecological outcomes. In intercropped plots, maize and sunflower acted as climbing structures for beans, while squash and zucchini suppressed weeds and retained soil moisture. Beans, in turn, appeared to improve the vigor of nearby crops, particularly maize, which exhibited greener, less stressed foliage when interplanted. These synergies contributed to more stable soil conditions and lower pest presence compared to monocultures, which lacked the protective and nutrient-sharing dynamics of a polyculture. The monoculture beds required more manual weeding in some cases and showed visible signs of nutrient stress and pest

vulnerability, despite similar inputs. Intercropping proved especially resilient under low-input conditions, with no synthetic fertilizers, minimal irrigation, and organically recycled soil. The consistent benefits across formats affirm the ecological soundness of interplant cooperation and validate the Three Sisters model as a low-input, high-resilience approach to sustainable horticulture.

Research Question 4: *Can crops like sunflower, cucumber, or zucchini effectively replace maize and winter squash in the Three Sisters model while maintaining its core ecological functions (support, nitrogen fixation, and ground cover)?*

Substitution trials yielded mixed but promising results. Sunflower successfully replaced maize in some systems, reaching sufficient height to support climbing beans and contributing to good system balance. Cucumber, while offering some ground coverage, was less effective than traditional squash due to its more upright growth habit and less dense foliage. However, zucchini, trialed as a bush-type squash substitute, performed very well. It provided broad, low-lying leaves that effectively suppressed weeds and did not require trellising, making it ideal for smaller spaces or container systems. These findings suggest that functional substitution is possible within the Three Sisters framework, especially when crop traits are carefully matched to system roles. Success depends heavily on variety choice, planting timing, and spatial dynamics. While some replacements may require adjustments, they offer flexibility for adapting the model to diverse climates, goals, and space constraints.

5.8 Future Directions

Future research could explore the scalability and long-term sustainability of container-based Three Sisters systems, especially in the context of urban living, land scarcity, and food insecurity. As cities grow and arable land becomes more limited, the ability to grow food on balconies, rooftops, or even windowsills becomes increasingly important. Investigating the productivity, soil longevity, and nutrient cycling of intercropped container gardens over multiple seasons could provide insight into how these compact systems can contribute to local food resilience and reduce reliance on industrial agriculture. This is particularly relevant for communities with limited access to fresh produce or space for traditional gardening.

Another promising direction is to expand biodiversity within the Three Sisters model by incorporating additional “sisters” as companion species. This could include pollinator-attracting flowers like nasturtiums or calendula, pest-repelling herbs like basil or marigold, or even nitrogen-boosting ground covers such as clover. Such integrations could not only support ecosystem services like pollination and pest control but also enhance soil structure and plant resilience.

Studying these biodiversity-enhanced versions of the Three Sisters could offer valuable lessons in regenerative design and polyculture efficiency, especially under organic or low-input conditions.

Further study is also needed on the use of crop substitutions within the Three Sisters framework. While this project explored sunflower and cucumber as potential replacements for maize and squash, additional combinations could be tested, such as okra, peas, or even edible perennials like rhubarb or ground cherry, depending on climate and goals. It would be important to examine not just the growth success of these alternatives, but whether they fulfill the original system's core functions of structural support, nitrogen fixation, and ground cover. Different combinations may work better in certain climates or spaces and may open up entirely new ways of adapting the Three Sisters model for diverse cultural and agricultural contexts.

Finally, future experiments should more systematically evaluate timing strategies. This study found that beans often struggled to establish before being shaded out by squash, and in some beds, corn would have benefited from earlier planting. Testing staggered sowing times, such as starting maize or sunflower a week earlier than squash and beans, or starting beans indoors for transplanting, could improve the establishment of each crop and enhance system balance. Fine-tuning the planting sequence to maximize cooperation and minimize competition could make the model more reliable and productive, especially for new growers or educational settings where demonstration and success are key.

6. Conclusion

This thesis examined modern interpretations of the traditional Three Sisters intercropping system, with a focus on its viability as a sustainable polyculture adapted for urban and northern climates. Through a comparative observational study across four growing environments (greenhouse bathtubs, outdoor raised intercropping beds, large container pots, and monoculture beds) the research explored how this time-tested Indigenous method could be reimagined for contemporary needs in peri-urban Sweden.

The results show that when thoughtfully adapted, the Three Sisters model remains ecologically functional and agriculturally productive, even in non-traditional formats. The greenhouse bathtubs, in particular, supported robust plant growth, interplant cooperation, and strong weed suppression, demonstrating how controlled microclimates and reused materials can support low-input, high-resilience food systems. Crops fulfilled their intended ecological roles: maize and sunflower provided vertical support, beans appeared to enhance nitrogen availability, and squash (or zucchini) offered effective soil coverage. Although growth in container pots was more limited, the results suggest that with proper crop selection and improved placement (such as on balconies, rooftops, or sunrooms) container-based Three Sisters systems could offer a compact, sustainable solution for food production in urban settings.

This research highlights how traditional knowledge can be transformed into practical models for regenerative, space-efficient gardening in cities and northern environments. By using repurposed materials, adapting crop choices to shorter seasons, and designing systems to suit constrained spaces, the Three Sisters approach becomes more than just a historical curiosity, it becomes a tool for building climate-resilient and socially inclusive food systems. Moreover, the project demonstrates the power of polyculture in fostering plant health, reducing pests and weeds naturally, and minimizing the need for synthetic inputs.

While the study was limited by its seasonal duration and largely qualitative data, it points to promising directions for future research and practical application. With further refinement, the Three Sisters system has the potential to serve as a model of sustainable polyculture that bridges ancestral wisdom with the pressing environmental and social demands of today's urbanized, climate-challenged world.

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Popular science summary

What happens when you combine ancient farming wisdom with modern containers like bathtubs and garden pots? This thesis explores exactly that: using the Indigenous Three Sisters planting method (corn, beans, and squash grown together) in small, sustainable garden setups adapted for life in Sweden.

The Three Sisters system, long used by Indigenous communities in North and Central America, is not just about growing food, it's about letting plants help each other. Corn stands tall and gives beans something to climb. Beans return nitrogen to the soil. Squash spreads out and shades the ground, keeping weeds away and moisture in. It's an elegant, cooperative system that needs little outside help.

In today's world of climate change, shrinking garden space, and the need for more local food, this old idea has become new again. My study tested the Three Sisters in four types of growing setups: inside reused bathtubs in a greenhouse, in outdoor raised beds, in large outdoor pots, and as a comparison, single crops grown alone in traditional beds. I also tried swapping out some crops to see if sunflowers, zucchini, or cucumbers could take the place of corn or squash.

The results? The greenhouse bathtubs grew the strongest and healthiest plants, with excellent weed control and few pests. The containers and raised beds also worked well, though timing and plant choice mattered a lot. The worst performers were the monoculture beds, where each crop grew alone. These had more pest problems, weaker plants, and dried-out soil in most beds. The experiment showed that even in northern climates like Sweden, and even in small spaces like balconies or backyards, this ancient system can thrive with little input.

The big takeaway is that the Three Sisters method isn't just history, it's a smart, sustainable, low-input, and low-cost way to grow food. It uses plant teamwork to save space, protect the soil, and reduce the need for fertilizers or pesticides. That makes it a great option for urban gardeners, schools, or anyone wanting to grow food in a better way. And with a bit more experimentation, like adding flowers to attract pollinators or adjusting planting times, it could become an even more powerful tool for future farming.

Appendix 1



Figure 1. Greenhouse bathtubs layout (mid-July).



Figure 2. Greenhouse bathtubs (early August).



Figure 3. Greenhouse bathtub crop cooperation 1.



Figure 4. Greenhouse bathtub crop cooperation 2.

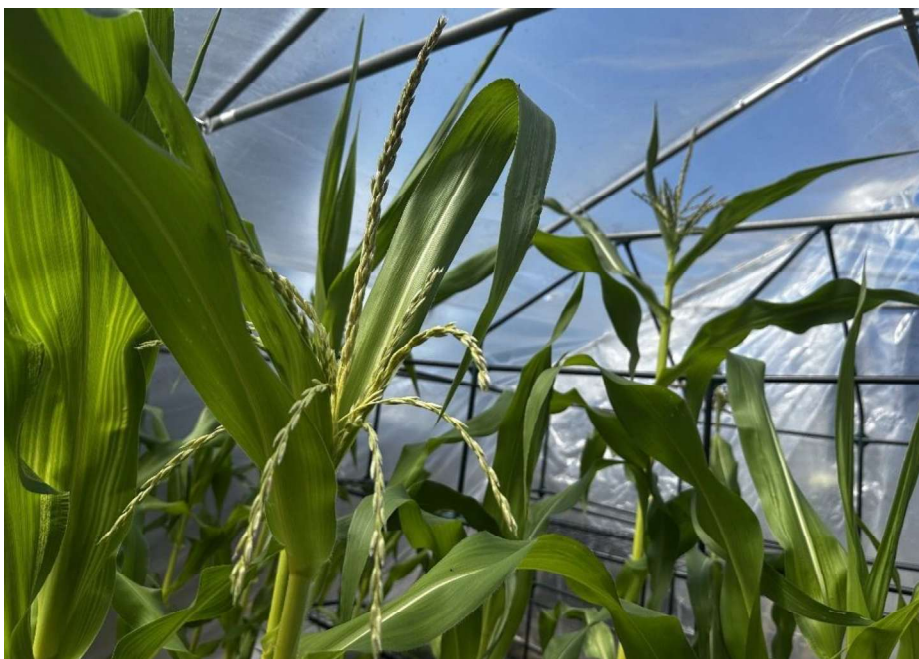


Figure 5. Greenhouse bathtub maize tassel growth.



Figure 6. Greenhouse bathtub squash flowering and fruiting growth.



Figure 7. Greenhouse bathtub sunflower growth with climbing beans.



Figure 8. Greenhouse bathtub sunflower three sisters' cooperation and flowering.



Figure 9. Greenhouse bathtub sunflower head growth.



Figure 10. Outdoor raised bed intercropping.



Figure 11. Outdoor raised bed intercropping with crop cooperation.

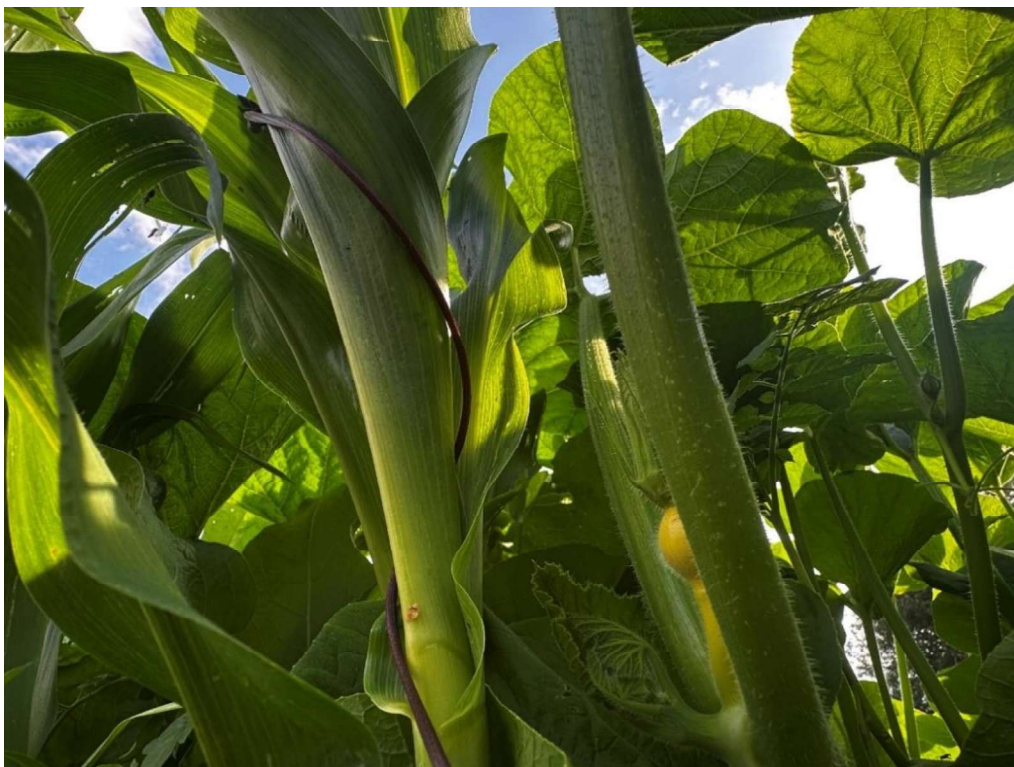


Figure 12. Outdoor raised bed intercropping with close-up of crop cooperation and fruit growth.



Figure 13. Outdoor container pot intercropping.



Figure 14. Outdoor container pot intercropping with zucchini (mid-July).



Figure 15. Outdoor container pot intercropping with zucchini (early August).



Figure 16. Outdoor container pot intercropping with cucumber.



Figure 17. Outdoor raised bed monoculture of maize.



Figure 18. Outdoor raised bed monoculture of climbing beans.



Figure 19. Outdoor raised bed monoculture of squash with signs chlorosis and leaf damage.



Figure 20. Greenhouse bathtub pest damage and traces.

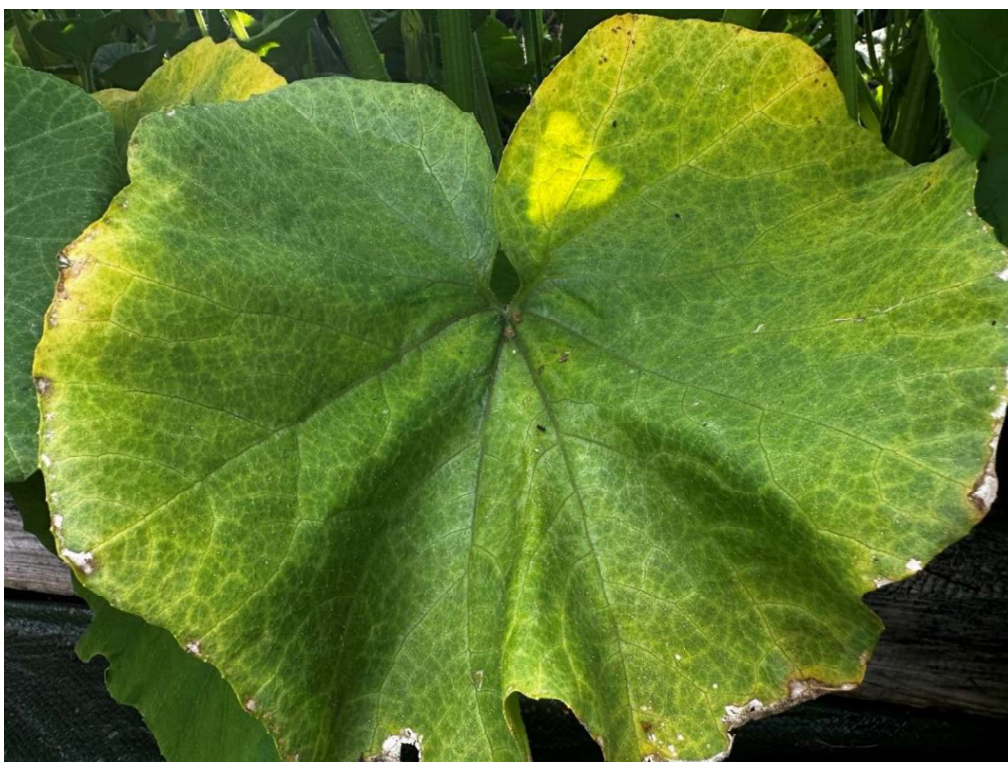


Figure 21. Outdoor raised bed monoculture showing signs of chlorosis and leaf damage.

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