Chapter

Solanum tuberosum Cultivation Using Nitrogen Recovered from Local Wastewater

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Abstract

This chapter presents an approach to recover nitrogen from human waste-water at local-scale for cultivation of *Solanum tuberosum* (potato) as food crop. Nitrogen capture is by ion exchange of ammonium (NH_4^+) onto zeolite, a natural low cost mineral which is available worldwide. A coupled process is described in which waste-water ammonium is sorbed to granular zeolite, biologically extracted (desorbed), and used to support *Solanum tuberosum* growth in fill-and-drain or irrigation cultivation. The system employs separate components to optimize conditions for ammonium sorption (anaerobic ion exchange), desorption (aerobic bioextraction), and cultivation (flexible timing of water and nitrogen supply and nutrient recycle). System architecture provides a low cost and readily implemented system for highly efficient nitrogen capture and incorporation into potato tuber. The nitrogen recycle system enables sustainable local-scale intensification of *Solanum tuberosum* production and enhanced food security through use of a reliable local nutrient supply. Metrics are presented for per capita tuber production, land area, and productivity. A system design is presented with a path forward for demonstration and development.

Keywords: wastewater, nitrogen, resource recovery, ion exchange, plant nutrient, *Solanum tuberosum*

1. Introduction

The challenge of feeding the world's population requires sustainable intensification of food production– producing more food from the same amount of land with fewer external inputs and less profound negative effects on the environment [1]. Potato (*Solanum tuberosum*) has an important role to play in sustainably increasing food supply. More than a billion people worldwide eat potato (*Solanum tuberosum*) and potato consumption is steadily expanding in the face of population growth and food security needs [2]. Potato is the world's number one non-grain food, with a global crop production of 370 million metric tons in 2019 cultivated on 17.3 million ha [3]. The recent *State of the World* report by FOA stated that the cost of food is a significant factor in global food security and low levels of productivity are a significant barrier to lower costs [3]. Regional potato yields range widely, from 50 tons per hectare (t/ha) and greater in high-input agricultural systems to less than 0.6 t/ha in subsistence cropping with minimal fertilizer use [4]. Nitrogen (N) is a key nutrient required for *Solanum tuberosum* growth and is the fertilizer component that must be

supplied in greatest quantity [5]. Nitrogen is essential to vegetative growth, protein synthesis, high potato yields and optimum crop quality [6]. Wastewater is a reliable local source of nutrients, and capturing nitrogen from wastewater and directing it to potato cultivation could increase productivity with low input costs. Since potato prices are often determined by local production costs [7], use of wastewater as locally available nitrogen source merits serious consideration.

2. Nitrogen for *Solanum tuberosum* production

Solanum tuberosum crop yield and quality are mostly dependent on the availability of nutrients and adequate moisture in the growth medium [8, 9]. Nitrogen is a major required macronutrient for *Solanum tuberosum* production and is essential to vegetative growth, protein synthesis, and high potato yields and quality [5, 6, 10, 11]. While potato consumption is steadily expanding in developing countries, more rapid expansion of supply is desirable to for adequate world food supply [2]. According to FOA, limited levels of productivity are a significant barrier to the lower costs needed to increase global food security [4]. However, where low input or subsistence cropping is employed, potato yields are much lower (< 5 t/ha) versus yields of 50 t/ha or more in high-input agriculture [3].

Human waste contains large quantities of nitrogen and other growth nutrients for *Solanum tuberosum* production. Where toilet systems are installed, human waste takes the form of wastewater, which is locally produced and continuously available. Wastewater treatment can supply low cost nitrogen and other nutrients at low cost. Coupling wastewater treatment with resource recovery for potato production can provide a system to realize the potential of *Solanum tuberosum* to increase global food security. Modern high-input agricultural practices contribute significantly to human alteration of the global nitrogen cycle [12]. Use of human waste for *Solanum tuberosum* production assists in the need to transform food production systems [4] and the UN sustainable development goals of higher standards of sanitation [13]. The use of controlled wastewater systems to deliberately recover nitrogen for potato production also reduces nitrogen losses to the environment and degradation of water quality [14].

The composition of major elements in potato tubers is listed in **Table 1** along with per capita generation rates for humans estimated from detailed studies of urine and fecal composition and generation rates [18]. Potato composition estimates were made from compositing multiple literature sources [11, 15–17]. Three major growth

Element		Potato tuber g/kg[1]	Human waste g/cap-day[2]
Nitrogen	N	3–14	12.80
Phosphorus	P	2.6–3.2	2.51
Potassium	K	2.9–13	2.78
Magnesium	Mg	0.21–1.3	0.35
Calcium	Ca	0.05–0.17	1.21
Iron	Fe	0.007–0.023	30.00
Sodium	Na	0.034–0.070	0.80

[1]*Millard [11], El-Latif et al. [15], Beldjilali et al. [16], Burrowes and Ramer [17].*
[2]*Estimated from Rose et al. [18].*

Table 1.
Element composition in potato tubers and human waste generation.

elements (N,P,K) are required for *Solanum tuberosum* propagation and tuber quality [19]. N, P, and K elements are present in large quantity in human waste (**Table 1**). Nitrogen (N) is the mineral nutrient most commonly deficient in agricultural soils [20] and a major determinant of tuber yield and quality [21–23]. The capture of wastewater nitrogen with zeolites and its recycle into plant protein is the major focus of this chapter. Positively charged elements in wastewater (K^+, Ca^{+2}) can also participate in ion exchange sorption and desorption cycles on zeolite [24, 25]. The provision of bulk wastewater storage in the system design described in this chapter can also be used as a source for other growth nutrients.

Wastewater is widely used for both irrigation and as nutrient source in agriculture, where the degree of treatment affects plant productivity and soil quality [26]. Wastewater agricultural uses include conventional field cropping [27], aquaponics [28] and hydroponic growth systems [29]. This chapter presents a system in which nitrogen is separated from the bulk wastewater to enable its deliberate and controlled supply for *Solanum tuberosum* cultivation.

Nitrogen is essential for conversion of solar energy into carbohydrates that are stored in the tuber. Proper nitrogen supply is needed for high yields and potato quality [30, 31]. It is desirable to match the timing of nitrogen supply with specific growth stages. Potato development generally follows sequential stages of 1. sprout development, 2. vegetative growth, 3. tuber initiation, and 4. tuber bulking. Nitrogen demand is low in the first month after planting (sprout development) and high in tuber initiation and bulking stages. The timing of growth stages is approximate and varies with environmental conditions and cultivars, and a nitrogen supply system must have a flexible nitrogen delivery rates to meet a range of plant growth needs.

For the recovery of wastewater nitrogen for potato production, it is desirable that the system reduce nitrogen losses to the environment such as occur with widely used soluble nitrogen fertilizers [32, 33]. Environmental losses can be minimized with a system that captures wastewater nitrogen on zeolite for its controlled release to match plant metabolic needs, as by a cultivation system that collects and recycles water.

Soil moisture affects the growth and yield of potato crops from both micro and seed tubers, and can soil water stress from lower irrigation rates can lead to lower tuber yields [34]. A system to capture nitrogen for *Solanum tuberosum* production must also supply adequate water throughout potato growth stages. The potato growth system described in this chapter includes storage of bulk treated wastewater that can be used for water consumptive demand and to supply nutrients other than nitrogen.

3. Capture of wastewater nitrogen with granular ion exchange media

Nitrogen in sanitation water is primarily ammonium (NH_4^+) and organic nitrogen and the organic nitrogen form is converted to NH_4^+ in anaerobic treatment [35]. Ammonium nitrogen in wastewater can be sequestered onto zeolites, natural low cost minerals with ion exchange properties which are available worldwide [36, 37]. Sorption of NH_4^+ by cation exchange zeolites is effective under anaerobic conditions [38]. Anaerobic treatment of sanitation water and NH_4^+ removal by ion exchange can comprise an integrated and low cost system to recovery of nitrogen from human sanitation water for potato production [39, 40].

Zeolites The sequestration of ammonium ion has been reported for a wide variety of natural zeolites, including salt activated Chinese (Hulaodu) zeolite [41], locally sourced zeolite in South Africa [42], natural Iranian zeolite [43, 44], Carpathian

clinoptilolite [24], Malaysian zeolite [45], Doganteppe Turkish zeolite [46], natural Australian zeolite [47], natural Turkish (Yıldızeli) zeolite [48], and Serbian clinoptilolite [49].

In addition to NH_4^+, potassium ion (K^+) can also be sequestered by natural cation exchange zeolites, and desorbed [25, 45]. Potassium is a significant elemental component in potato tuber (**Table 1**). Potassium and other cations may participate along with NH_4^+ in the processes of capture and release from zeolite and cation sorption of cations is competitive [50]. Wastewater constituents other than ammonium and prominent cations can also be removed from wastewater by ion exchange though there is limited research in this area [51, 52]. Zeolite as soil amendment enhances grain crop yield and reduces nitrate leaching [53]. Zeolite-sorbed wastewater nitrogen to enhanced growth of *Arthrospira platensis* cyanobacteria [49]. Zeolite was used to separate NH_4^+ from wastewater, which was substantially recoverable and useful for slow release nitrogen fertilizer [54].

Anaerobic Baffle Reactor The Anaerobic Baffle Reactor (ABR) is suitable as for primary sanitation water treatment prior to granular zeolite media. The Anaerobic Baffle Reactor (ABR) is an anaerobic solids blanket bioreactor with multiple upflow chambers that are hydraulically linked through alternating downflow plena [55]. Flow between ABR chambers does not require pumps and is suitable for primary anaerobic treatment of sanitation water [56]. ABR has been applied in ecological sanitation systems for passive, low maintenance primary treatment of sanitation water in low-income communities [57, 58]. The solids blankets in anaerobic upflow reactors foster sedimentation, filtration and colloidal retention of sanitation water components, as well as anaerobic biological treatment [59–61].

Field IX Prototype The integration ion exchange recovery of wastewater NH_4^+ with anaerobic pre-treatment of sanitation water was verified in a field prototype study [62]. The IX reactor contained three upflow chambers, each preceded by a downward plenum and each containing granular porous zeolite (**Figure 1**). IX chambers retain NH_4^+ by ion exchange and function as anaerobic biofilters [35]. Design features of the IX prototype are listed in **Table 2**. The IX reactor had a liquid empty bed volume including down flow channels of 41.7 L. Specific construction details were presented previously [35]. Zeolite was NV-Na Ash Meadows Clinoptilolite (St. Cloud Mining Company), selected for its low cost, availability in multiple grain sizes, and its stable long-term supply. Nv-Na properties are listed in **Table 3**. Nv-Na is a hydrous sodium aluminosilicate with high specific surface area (40 m^2/g) and bulk density of ca. 800 kg/m^3. The major chemical components are 69.1% SiO_2, 11.9% Al_2O_3, 3.8% K_2O, and 3.5% Na_2O. According to the manufacturer, Nv-Na has a clean water Cation Exchange Capacity (CEC) of 1.85 meq./g (185 cmol(+)/kg). Media in Chamber 1 consisted of 100% of US 4x8 Nv-Na (2.38–4.75 mm). Media in Chambers 2 and 3 was 100% US 8x16 Nv-Na (1.18–2.38 mm).

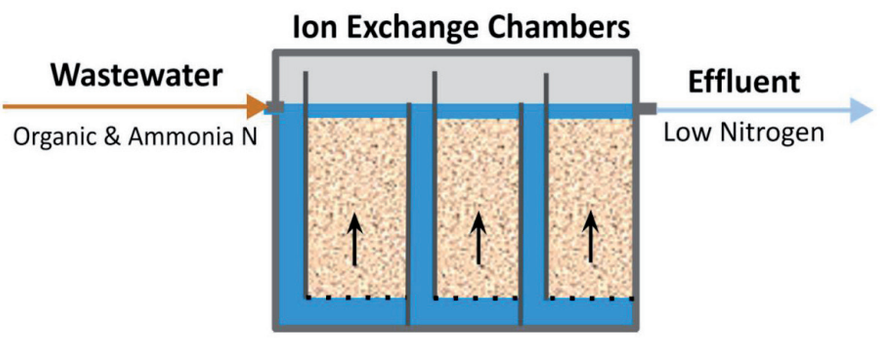

Figure 1.
IX field prototype wastewater nitrogen capture.

Chamber	Media	Empty Bed Volume (L)	Empty Bed Residence Time (hour)[2]	Zeolite Mass (kg)
	Zeolite[1]			
1	U.S. 4 × 8	15.9	37.4	6.55
2	U.S 8 × 16	13.2	31.1	7.18
3	U.S 8 × 16	12.6	29.6	5.13
Total		41.7	98.2	18.8

[1]*Clinoptilolite, 1.85 meq/g CEC.*
[2]*10.2 L/d mean flowrate.*

Table 2.
Prototype IX design.

Grain size, mm	1.5–4.5
Color	Tan - Green
Pore Volume, %	1500%
Pore Diameter, Angstrom	4.0
Specific Surface Area, m^2/g	40
Bulk density, kg/m^3	820
Solid Density, kg/m^3	1,600
Ion Exchange Capacity, meq/g	1.85

[1]*https://www.stcloudmining.com/.*

Table 3.
Properties of granular Clinoptilolite.

Field testing was conducted in Maryland at the Mayo Water Reclamation Plant in Anne Arundel County. The Mayo facility receives treats a daily flow of 1,890 m^3/day primary treated household wastewater from 3,500 residences. Influent to IX was pumped from the plant influent wet well. Zeolite was placed in the three Chambers on Day 0. The goal of initial operation was to establish the validity the IX concept and confirm its central treatment architecture. The IX prototype was dosed once per hour by peristaltic pump at 10.2 L/d from start of operation to Day 319 (4.1 day empty bed HRT. The prototype operated over an ambient temperature range of 7–24°C throughout the study. Flowrate was increased on Day 320 to accelerate the breakthrough of NH_4^+ and exhaust the sorption capacity of the IX media. Flowrate was increased to 36.5 L/d on Day 320 (factor of 3) and 71.4 L/d on Day 344 (factor of 7).

IX Prototype Performance A characteristic profile of nitrogen species through IX chambers after initial operation was established is shown in **Figure 2**. The predominant nitrogen forms in IX influent are Organic Nitrogen and ammonium, which are substantially decreased by IX Chamber 1 through Day 85. Nitrate and nitrite are not present through the IX system. Monitoring results are summarized in **Table 4** for the monitored period of Day 1–214 well before breakthrough of NH_4^+ past Chamber 1. For the Day 1–214 period, TN removal was greater than 95%. The retention of NH_4^+ by ion exchange was the major factor that determined Total Nitrogen (TN) removal by IX throughout the study. Through the entire prototype operation, Organic Nitrogen (ON) remained below 2 mg/L in IX effluent and nitrate and nitrite were below detection levels. Effective NH_4^+-N removal was calculated from effective influent NH_4^+-N and measured effluent NH_4^+-N, where effective influent NH_4^+-N is the sum of measured influent NH_4^+-N and the change in ON across the IX reactor. Effective NH_4^+-N reduction was virtually complete

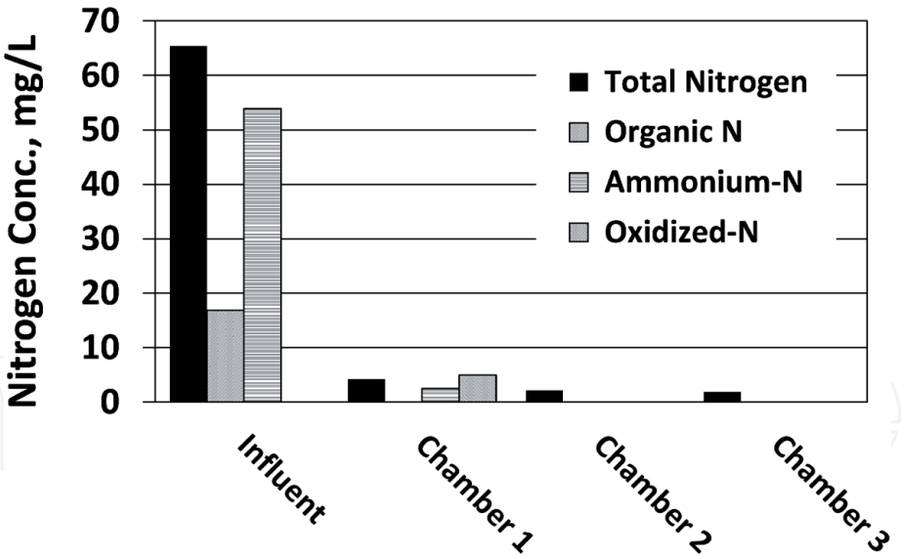

Figure 2.
IX nitrogen removal profiles (day 0–85).

Nitrogen fraction	Mean Influent	Mean Effluent	% Removal
Total	54.0	1.3	97.6
Total kjekldahl	54.0	1.9	96.5
Organic	14.3	1.3	91.2
Ammonia	42.7	0.014	100.0
Nitrate - nitrite	0.02	0	—

Table 4.
IX nitrogen removal performance (day 1–214).

from Day 1–214 (**Table 4**). For the extended operation period (Day 215–355), mean TN removal was affected by NH_4^+ breakthrough; mean removals of TN and NH_4^+-N were 29.7% and 12.1%, respectively. IX treatment substantially reduced wastewater organic matter, as indicated by a mean COD reduction of 58.7% (Day 1–214). IX effluent pH remained circumneutral throughout the study and ORP in chamber effluents remained negative.

The timecourse of ammonium nitrogen in IX chamber effluents is shown in **Figure 3**. Chambers 1, 2 and 3 showed sequential breakthrough of NH_4^+ over extended operation. IX effluent NH_4^+ (Chamber 3) remained below 0.07 mg/L through Day 214 and was ca. 2 mg/L through Day 319 after substantial breakthrough had occurred in Chambers 1 and 2 (**Figure 3**). The timecourse of NH_4^+ in chamber effluents during continuous flow showed the NH_4^+ breakthrough fronts as sorption capacity became exhausted. Flow rate was increased from Day 320 to the end of operation on Day 355. Effluent NH_4^+ increased rapidly after flow rate was increased and continued through Day 355. At the end of operation, NH_4^+ levels in the effluents of Chambers 1, 2 and 3 were at or near the influent NH_4^+ level, suggesting complete exhaustion of the ion exchange media in all IX chambers. The effective ammonium exchange capacity was 11.3 mg NH_4^+-N/g dry weight (0.81 meq/g), or 44% of the Nv-Na clean water capacity. For the Mayo wastewater matrix, effective Nv-Na capacity for NH_4^+ was 16% lower than that found in a Florida onsite wastewater IX [35]. Lower capacity in the Maryland IX was possibly due to competitive ion exchange. Calcium and sodium are prominent

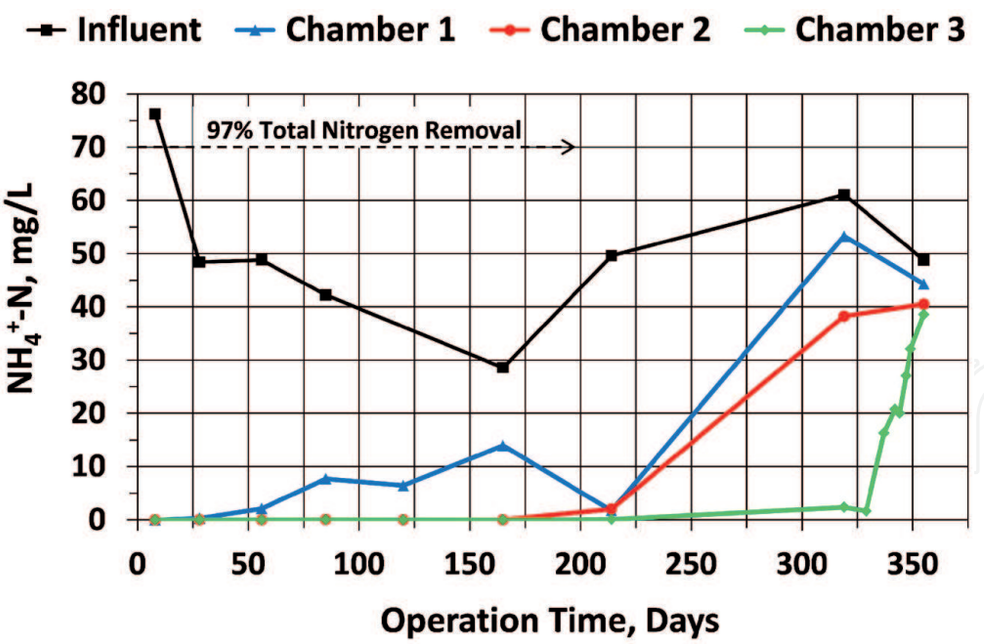

Figure 3.
Time Profiles of Ammonium Nitrogen through IX Chambers.

competing cations that could affect NH_4^+ capacity [44]. Jama and Yucel, 1989 developed forward and reverse ion-exchange isotherms for clinoptilolite and binary solutions of NH_4^+/Ca^{+2} and NH_4^+/Na^+, at a total ionic concentration of 0.10 eq/dm^3. Significant reductions in NH_4^+ capacity were observed for both competing Ca^{+2} and Na^+ ions. The conductivity of Maryland wastewater (3,650 uS/cm) suggested that NH_4^+ capacity might have been reduced by competing cations, possibly from collection system infiltration in this coastal location or Na^+ from water softener backwash.

Flow rate increases of 3 and 7 times were imposed after Day 320 (**Figure 1**) and IX Empty Bed Contact Time was decreased to as low as 0.6 d. The IX process showed no observable adverse effects on operation during this period, other than the intended acceleration of NH_4^+ breakthrough. This suggests that IX performance can be robust and resilient when challenged by the significant flow variations that are typical of local sanitation systems. IX is a highly effective system for local nitrogen recovery. It is passive, mechanically simple, has no inherent energy need, and requires little operator attention. The IX process is resilient and amenable to seasonal operation. IX a highly appropriate technology for local application and provides a new option for locations where wastewater nitrogen removal is critical. Nitrogen captured in IX can be recovered for recycling.

A field IX prototype identical to the Maryland prototype was operated in Florida. The Florida IX prototype also treated actual wastewater that had received anaerobic primary treatment. Total Nitrogen in sanitation water was reduced by over 95% by both prototypes. Nitrogen removal capacities of clinoptilolite zeolite (1.85 meq/g CEC) are shown in **Table 5** [35, 62]. Retention capacity of ammonium nitrogen was 13.5 and 11.3 g NH_4^+-N per gram clinoptilolite, or 52.1 and 43.6% of clean water CEC. The effective ammonium capacity was ostensibly reduced by competing cations (Na^+, Ca^{+2}) or other factors. Ammonium capacity reductions from competing cations would be expected to generally occur for various zeolites from different regions and sources. The operational ammonium capacity shown by the prototypes, however, is quite useful technologically for sequential sorption and bioextraction of nitrogen for plant growth. In developing countries, low per capita water usage could result in higher nitrogen concentrations in wastewater and

Site Wastewater	County Park Residence and Day Lavatory, Florida	Influent to Maryland WWTP
Days Operated	662	355
Temperature Range, °C	23–31	7–17
Mean Influent Total Nitrogen, mg/L	44.2	56.0
TN Reduction, %		97.6
NH_4^+ Capacity, mg N/g dw	13.5	11.3
% of CEC	52.1	43.6

Table 5.
IX nitrogen removal performance and capacity.

possibly increase the competiveness of NH_4^+ sorption. It is noted high effectiveness of TN recovery by IX was maintained at temperatures of 7 to 31C (**Table 5**). Ammonium recovery by IX may be suitable across many climate zones.

Summary IX is a viable means to for recover of nitrogen from wastewater over extended periods. IX treatment of primary effluent sanitation water can recover nitrogen in a passive, mechanically simple process without pumps and sophisticated controls. The system recovers a high percentage of nitrogen, is reliable, and is effective at high and low temperatures. It is effective at varying flow rates, for discontinuous operation and, suitable to local scale deployment. Final effluent of IX treatment is low in total suspended solids (TSS) and low in five-day carbonaceous biochemical oxygen demand (C-BOD_5) as a measure of bulk organic oxygen demand [35].

Solute transport model A one-dimensional solute transport model that accounted for advection, diffusion & equilibrium adsorption was used to model the transport of NH_4^+ through ion exchange chambers [62]. In the z direction:

$$\frac{dC}{dt} = \frac{1}{R}\left(D\frac{d^2C}{dz^2} - v_o\frac{dC}{dz}\right) \tag{1}$$

where C = solute concentration (mg/cm^3 NH_4^+-N), t = time (d), D = hydrodynamic dispersion coefficient (cm^2/day), z = length (cm), and v_o = pore water velocity (cm/day). The dimensionless retardation factor R encompasses instantaneous adsorption equilibria between pore water and solid phase:

$$R = 1 + \frac{p\,K\,N\,C^{N-1}}{\grave{e}} \tag{2}$$

where p = solid phase bulk density (g/cm^3), K = solute distribution coefficient (L/kg), N = sorption parameter (−) and θ = porosity (cm^3/cm^3). Solution of the model employed an analytical solution for fully saturated flow through porous media [63].

Simulation of NH_4^+ transport The 1-D solute transport model (Eqs. (1) and (2)) model was used to predict the NH_4^+-N concentrations in the effluents of the three ion exchange chambers. The model was applied with z axis of zero at the entrance to the first ion exchange chamber (Chamber 1) and time zero on the day of zeolite placement into Chambers 1, 2 and 3. Parameters were estimated for initial

conditions and for each term in Eqs. (1) and (2). The simulation used the mean influent NH_4^+-N concentration of 52.0 mg/L that entered Chamber 1 through the study. The total mass of NH_4^+-N removed in IX operation was calculated as the difference between influent and effluent mass over 355 d of operation, which were estimated as the integrated areas under the influent and effluent time profiles of NH_4^+-N. The total NH_4^+-N mass removed divided by the dry weight of Nv-Na added to the three ion exchange chambers yielded a sorption capacity of 11.3 mg NH_4^+-N/g dw Nv-Na (0.81 meq/g) for the IX treating Mayo wastewater. The distribution coefficient of 218 L/kg was calculated from the clinoptilolite sorption capacity and the mean influent NH_4^+-N concentration. Linear sorption was assumed for the simulation (N = 1 in Eq. (2)). A media porosity of 0.45 was used based on manufacturer information and the retardation factor was 389 (dimensionless). Analytical solutions were calculated using 1-D path lengths and pore velocities in each of chamber.

Simulated breakthrough of NH_4^+-N in Chambers 1 through 3 are shown in **Figure 4** along with measured NH_4^+-N concentrations. The 1-D model provided a generally reasonable simulation of NH_4^+-N breakthrough in IX chambers. Zeolite is predicted to approach exhaustion on Days 300, 420, and 540, respectively, in Chambers 1, 2 and 3. Monitored chamber breakthroughs occurred sequentially as expected and in accord with the simulation. The 1-D model approximated measured NH_4^+-N values for Chambers 1 and 2 throughout, and for Chamber 3 up until Day 320. The monitoring data for Chambers 1 and 2 are predicted fairly well by the 1-D simulation. Model predictions are quite acceptable considering that that the 1-D solute transport solution employs a constant influent concentration versus the actual influent nitrogen level that varied significantly (**Figure 3**). The discrepancies between NH_4^+-N measured in Chamber 3 effluent versus the simulation model are due to the high increase in influent flowrate after Day 320, which invalidated the model assumption of constant flowrate and resulted in a much more rapid breakthrough of NH_4^+.

The general competence of the simulation illustrates that NH_4^+ retention by granular ion exchange media appears to be a tractable when treating actual onsite wastewater. Rational procedures for analysis, design, and monitoring can be developed for field deployments. NH_4^+ retention is the main factor affecting Total Nitrogen removal. Modeling and data suggest that operational methods can be

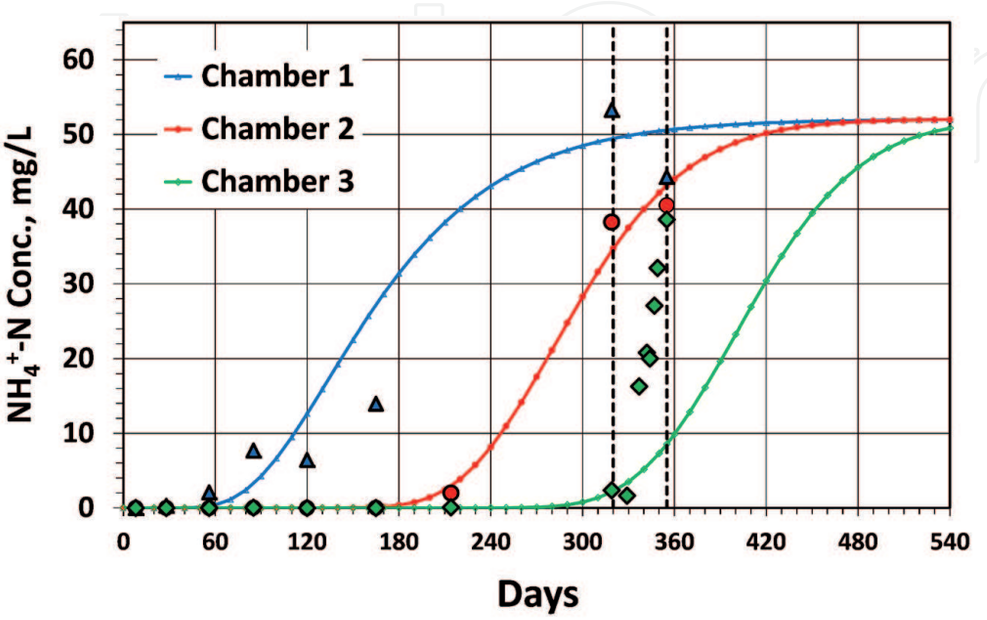

Figure 4.
Simulation model of ammonium ion breakthrough.

developed to optimize NH_4^+ retention, prevent nitrogen breakthrough and loss, cease wastewater flow to the ion exchange chambers, and initiate bioextraction of nitrogen from the spent media.

Simple field measurement of NH_4^+ in the IX chamber effluents can assess media exhaustion in each chamber, determine location of a breakthrough front, and assist on determining when to cease operation and switch to an alternate parallel IX train.

4. Incorporation of wastewater nitrogen into *Solanum tuberosum*

Bioextraction Incorporation of recovered wastewater nitrogen requires desorption of NH_4^+ from zeolite and supplying nitrogen to plant roots. Biological extraction couples biological oxidation of ammonium to nitrate (nitrification) with ammonium desorption from zeolite. The driving force for desorption is affected by the sorption density of NH_4^+ in the zeolite and the concentration of NH_4^+ in bulk water in media pores or in film water on the media surfaces. Nitrification reduces the NH_4^+ concentration and increases driving force. Nitrification rates are affected by the population of nitrifying microorganisms, temperature, oxygen supply, and pH.

Bioextraction is accomplished by circulating extraction water through zeolite(IX) to simultaneously desorb and nitrify NH_4^+. In fill and drain bioextraction, water is pumped from a bioextraction reservoir in order to fill and saturate the IX media, which then passively drains back to the reservoir when pumping is discontinued. In *fill stage* the zeolite media becomes flooded (saturated) are remains so until pumping is discontinued. In *drain stage*, passive drainage begins at high rate and gradually declines, restoring unsaturated conditions until the next *fill stage*. The frequency, duration and magnitude of pumping in the *fill stage* are important operational features that determine the quantity and timing of water supply, the temporal extents of saturated and unsaturated conditions and their relative durations, and the oxygen supply regimes.

Nitrogen bioextracted from IX accumulates in the volume of bioextraction water, generally as ammonium (NH_4^+) or nitrate (NO_3^-). Oxygen is supplied by water added during the *fill stage* and in the *drain stage* by ingress of air into the unsaturated media. Nitrification consumes alkalinity, which may depress the pH of the bioextraction solution and inhibit nitrification. Sodium carbonate and sodium bicarbonate can be amended to the bioextraction water to prevent pH decline [64]. Ammonium is inhibitory to nitrification at high concentrations. The buildup of ammonium in the bioextraction reservoir can be limited by bleed off to a separate plant growth system. Bleed off of the bioextraction reservoir can also have alkalinity preservation consequences.

The requirements of zeolite bioextraction coupled to plant growth suggests two system architectures:

- *One stage*: direct fill and drain cultivation of potato in zeolite media
- *Two stage*: fill and drain bioextraction and separate stage potato production

In the *one stage* system, potato grows directly in the zeolite media bed used for recovery of wastewater nitrogen. The *two stage* system separates fill and drain bioextraction from plant growth. The *one stage* system requires less area and has less supported volume for IX media and plant cultivation. Plant growth in the *one stage* system is obligatorily conducted in fill and drain mode. Management of the bioextraction reservoir nutrient content, chemical composition, and plant water and growth requirements are more intricately related.

In the *two stage* system, bioextraction can be optimized independently of the requirements and constraints of plant growth. Plant growth can be accomplished either in fill and drain mode with highly porous media, or with more conventional soil based systems and irrigation practices. A separate nutrient reservoir can flexibly supply nutrients and water for plant growth requirements. The bioextraction reservoir and plant growth nutrient reservoir can be linked for more flexible control of nutrient content and chemical composition. *Solanum tuberosum* cultivation produces prolific underground biomass in addition to potato tubers. An advantage of the two stage system is that *Solanum tuberosum* is not cultivated directly in the granular ion exchange media. Subsurface plant biomass products such as fine micro-roots, plant mycelium, and other constituents would not remain in the IX media after harvesting. These plant products could hamper the ability to regenerate and reuse IX media for continuous future deployments.

Transmission of pathogens and other constituents are of concern when wastewater is used for irrigation of crops, as reported for sewage farming [65, 66]. A *two stage* system incorporates inherent transmission barriers because the bioextraction and plant growth functions are separated. *Solanum tuberosum* does not grow in the zeolite media through which wastewater has passed, and transfer of IX bioextraction water to the growth system is the only communication from IX to *Solanum tuberosum.* The *two stage* system also has opportunities to create additional barriers. A *one stage* system has fewer barriers to transmission than a *two stage* system.

Direct plant growth in zeolite The integration of recovery of wastewater nitrogen with zeolite with direct growth of food crop in zeolite media has been demonstrated for *Solanum lycopersicum* [62]. The coupled system for zeolite bioextraction and plant growth is shown in **Figure 5**. Fill-and drain experiments were conducted using spent zeolite that had reached its ammonium retention capacity when treating wastewater at the Mayo Water Reclamation Plant in Anne Arundel County, Maryland (described in previous section). Spent zeolite was removed from the three IX chambers, blended, and applied in parallel treatments. Plant growth experiments were conducted in flood-and-drain regime, with a dedicated bioextraction reservoir for each planting container. A *fill cycle* was initiated on 8 hour interval (3/day) for 35 min. Establish a 2 cm standing water column above the top of the media. After

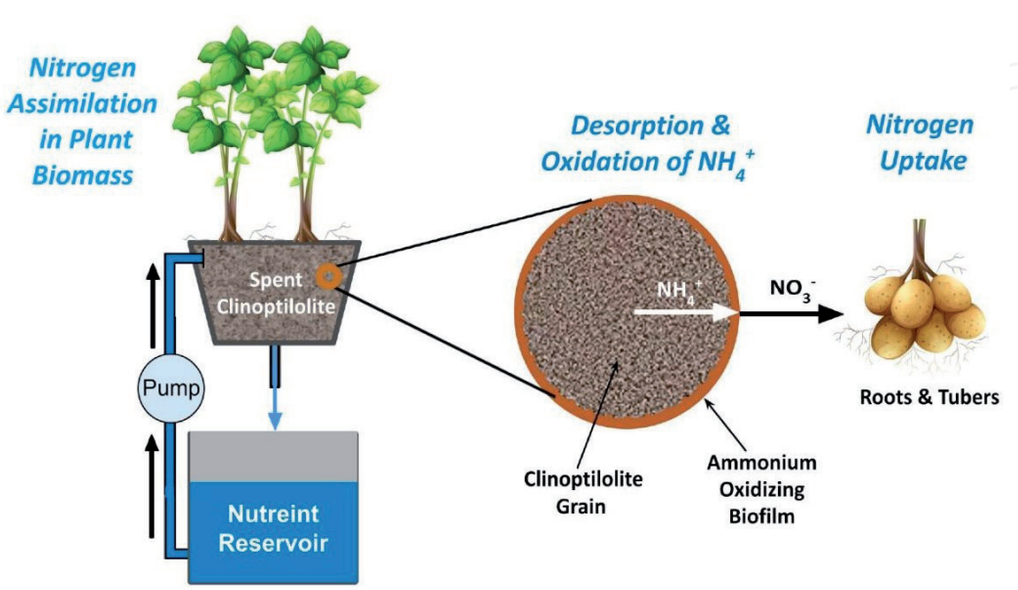

Figure 5.
Fill and drain cultivation with nitrogen from spent zeolite.

the 35 min. Fill period, water in the planting containers drained back to the bioextraction reservoir and unsaturated conditions in the media were restored.

A controlled growth chamber was used to conduct growth experiments. Parallel treatments were conducted using spent Nv-Na clinoptilolite and fresh expanded clay (**Table 6**). Each treatment consisted of a columnar planting container (21.3 cm diameter) with 12 cm media depth (3.3 L media volume). The bioextraction reservoirs served as source of external growth nutrients and enabled the nitrogen levels to be separately monitored for each treatment. Experiments were initiated by placing 15 *Solanum lycopersicum* (cherry tomato) seeds one centimeter below the media surface at the center of the planting containers. Operation of treatments was then commenced under identical conditions. Light was supplied uniformly to the growth chamber by a fluorescent 6400 K grow light fixture (Hydrofarm T-5), with a daily cycle of 12 h on/12 h off daily cycle. The Photosynthetic Photon Flux (PPF) was ~250 μmol/m^2-sec at 30.5 cm above the granular media surfaces, as measured with a quantum meter (Apogee MQ-200, Logan, Utah). The cultivation temperature varied between 13.8 to 17.7°C [62].

Bioextraction reservoir water differed in parallel treatments. The full nutrient suite contained N, P, K, Ca, Mg, and Si at the levels listed in **Tables 1**, and 10 ml/L of supernatant from an Anaerobic Baffled Reactor (ABR) treating municipal wastewater treatment plant influent. Treatment T1 had clean Nv-Na zeolite and received the full nutrient suite including synthetic nitrogen (**Table 1**). T2 received no added nutrients. T3 and T4 received no synthetic nitrogen. T4 received the full nutrient suite minus nitrogen, whereas T3 received only K and P (**Table 1**). Growth response of T4 versus T1 would ostensibly demonstrate if wastewater nitrogen on spent Nv-Na (T4) could be effectively recycled into *Solanum lycopersicum* growth. Bioextraction reservoir volumes at initial start-up were 7.57 L and the pH was adjusted to 5.9 ± 0.05. To maintain working volumes of at least 5.7 L, make-up water having the same nutrient composition as the starting solutions was added on

Treatment	**T1**	**T2**	**T3**	**T4**
Granular Media	Fresh Media	Spent Media from AN-IX Reactor		
% 4 × 8 clino	—	40	40	40
% 8 × 16 clino	60	60	60	60
% 3/8 exp. clay	40	—	—	—
Nutrient Supplementation	Full Suite	None	P & K only	Full Suite Minus N
Growth Media Ionic				
Composition, mM				
HNO_3	6.0	—	—	—
K_2HPO_4	0.5/1.5[a]	—	0.5/1.5[a]	0.5/1.5[a]
KCl	2.6	—	2.6	2.6
$CaCl_2 \cdot 2\ H_2O$	1.0	—	—	1.0
$MgSO_4 \cdot 7\ H_2O$	1.0	—	—	1.0
K_2O_3Si	1.0	—	—	1.0
$NaHCO_3$	6.0	3.0	3.0	6.0
ABR supernatant, ml/L	10	—	—	10

[a]*Before/after Day 63.*

Table 6.
Solanum Lycosperium growth on with spent Clinoptilolite.

Experiment Days 14, 28, 49, 63 and 81 listed in **Table 1**. After each make-up water addition, bioextraction reservoir pH was adjusted to pH 5.9 ± 0.05.

A comparative, non-destructive measure of plant growth for the parallel treatments was plant canopy volume. Significant differences in *Solanum lycopersicum* growth were observed (**Figure 6**). The greatest canopy volume was obtained in the T4, for which all nitrogen was provided by Nv-Na zeolite. Intermediate plant growth was obtained for treatments T1 and T3, which also received external nutrients, whereas plant canopy volume was minimal for T2, which received no external nutrients (**Figure 6**). Treatments T1 and T4 were identical with the exception of the supply synthetic nitrogen fertilizer to T1 versus growth of T4 in spent IX media without synthetic N. The greater growth of T4 versus T1 shows that nitrogen separated from human wastewater by IX can be directly recycled to production of *Solanum lycopersicum*. It also suggests that spent media may contain components other than nitrogen that are stimulatory to *Solanum lycopersicum* growth. Treatments T3 and T4 were both cultivated in spent IX media but only P and K nutrients were supplied to T3 (**Table 1**). Since both treatments would have had access to nitrogen from spent IX media, the lower canopy increase of T3 suggests that T3 growth may have been limited by trace inorganic nutrient supply or a component in ABR supernatant. The number of *Solanum lycopersicum* fruits and flowers in treatment T4 were over two times those of T1 at Day 93, which accords with the canopy volume comparison and further demonstrates that spent IX provides a favorable medium for plant propagation. The consumptive water use for crop production is a significant factor in many regions where water supplies are limited. Water use in parallel *Solanum lycopersicum* treatments was estimated by the recorded make-up volumes supplied to the bioextraction reservoirs. The increase in canopy volume on Day 93 per consumptive water use was equal to or greater for T4 (spent IX nitrogen) than synthetic nitrogen fertilizer in T1 [62].

The timecourse of NH_4^+ and NO_3^- in the dedicated hydroponic reservoirs of parallel *Solanum lycopersicum* treatments are shown in **Figure 7**. Bioextraction of ammonium ion initiated quickly and was substantial through 93 day (**Figure 6**). With spent IX media, nitrogen accumulated in the hydroponic reservoir solution as NH_4^+ and NO_3^- (NO_2^- was not detected). Spent zeolite treatments had the highest

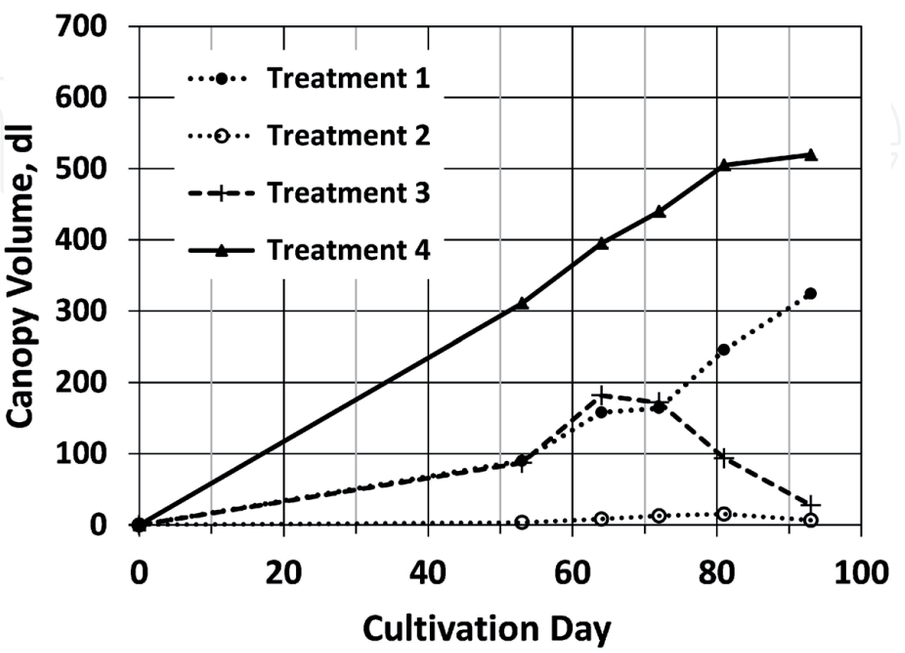

Figure 6.
Solanum Lycosperium canopy establishment.

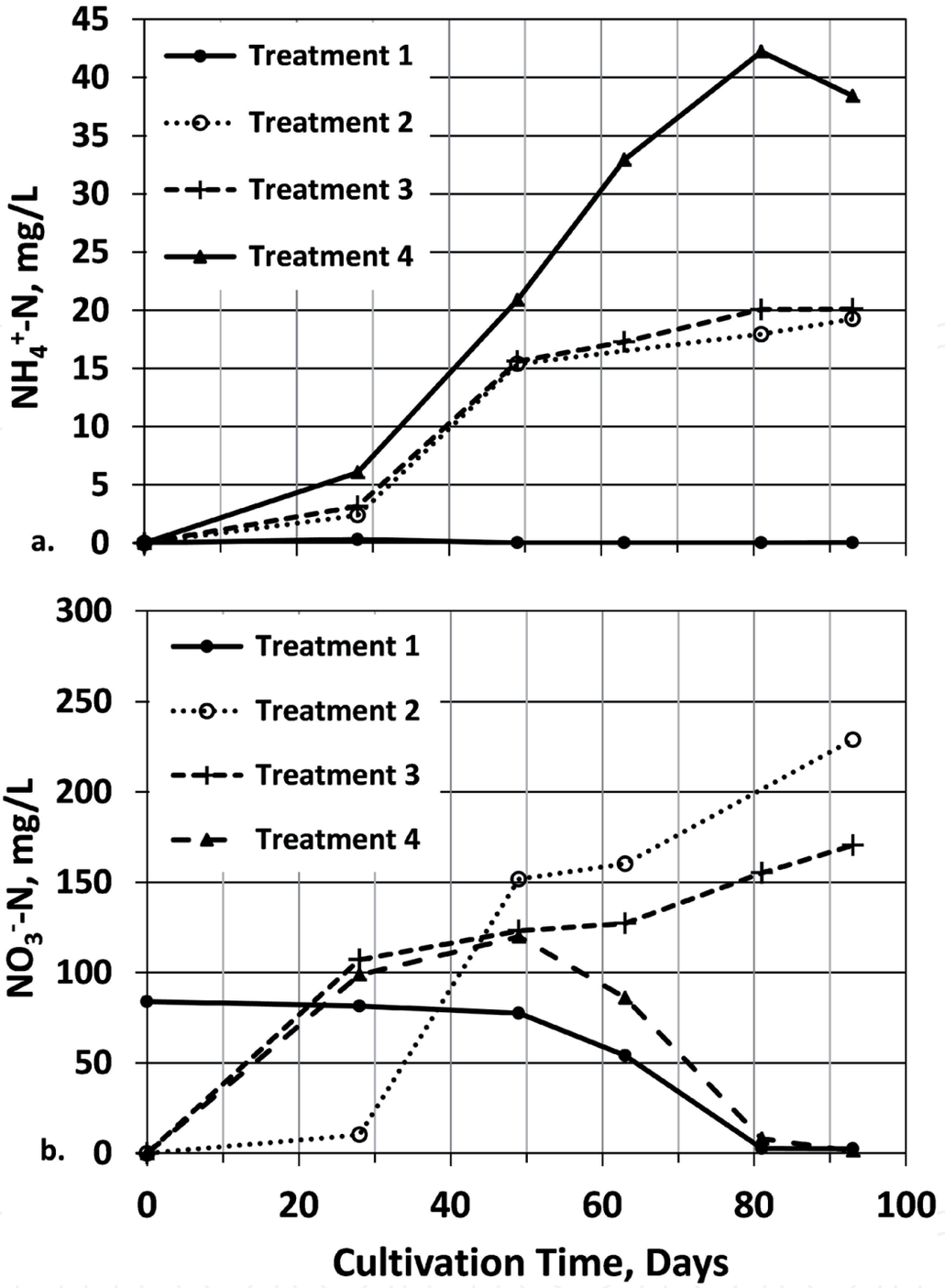

Figure 7.
Bioextraction and nitrification in reservoir nutrient solutions: a. Timecourse of ammonia and b. timecourse of nitrate in reservoir nutrient solutions.

NH_4^+-N concentrations (T4 > T3 > T2) with very low NH_4^+-N levels observed in fresh media of T1. In each of the treatments with spent IX, NO_3^--N increased to over 100 mg/L by Day 50, providing evidence that NH_4^+ in IX media was readily extracted and nitrified (**Figure 7b**). No deliberate microbial seeding was employed in T2, T3 and T4. NO_3^- levels in Treatments T2, T3, and T4 in were generally higher than NH_4^+ to Day 50, showing that nitrification rates kept up with the rates of NH_4+ extraction from the IX media.

Nitrification was slower to establish in T2, however, perhaps due to the lack of added external nutrients. After Day 50 NH_4^+-N in T4 reached substantially higher levels than T2 and T3 (**Figure 7a**), during which NO_3^- in T4 decreased substantially (**Figure 7b**). After Day 50, declining NO_3^- levels in bioextraction reservoirs

(**Figure 7b**) and highest increases in canopy volume (**Figure 5**) occurred for treatments T1 and T4, suggesting plant biomass assimilation of NO_3^-. T2 exhibited the highest NO_3^- levels, which might be explained by significant bioextraction from spent IX and limited plant growth due to the lack of external nutrients. The differences in *Solanum lycopersicum* growth and timecourse of nitrogen species in the bioextraction reservoirs illustrate the complex interactions that determine solution nitrogen levels and nitrogen availability in coupled bioextraction/plant growth systems. Nitrogen availability has important implications for plant growth in IX/hydroponic systems, as nitrogen levels and composition can affect growth rates and nitrogen allocation in leaves, stems and seeds. Further research is needed to optimize nitrogen availability in bioextraction/growth systems.

This study verified that wastewater nitrogen sorbed on zeolite IX process can be directly recycled for growth of *Solanum lycopersicum (cherry tomato)*. The bioextraction/growth system has potential for cultivation of *Solanum tuberosum (potato)*, another edible plant in the nightshade family. Unlike the harvestable component of *Solanum lycopersicum*, however, *Solanum tuberosum* tubers lie below the surface of the planted medium. The significance of subsurface tuber production to potato production in a one stage bioextraction/growth is a matter that bears consideration. For *Solanum tuberosum, the* separation of the bioextraction and plant growth functions in a two stage system may be warranted.

Separate Stage Bioextraction A separate system for bioextraction of nitrogen from spent media can be optimized without the constraints of integrated plant growth. Optimization methods include the frequency, duration and magnitude of fill and drain cycles, seeding of spent IX media with nitrifying bacterial cultures, and alkalinity supplementation. Report in this arena come from wastewater treatment where zeolites are integrated into aerobic treatment processes to enhance nitrogen removal. Zeolites serve the two functions of ammonium retention through ion exchange and as solid substrate for attached growth of nitrifying microorgansms. A single reactor, two mode process for ammonium removal from secondary wastewater effluent using zeolite as the carrier for nitrifying biomass was proposed [67]. In the batch bioextraction mode, a nitrification rate of 6 g NH_4^+-N/L reactor-day (0.44 mg NH_4^+-N/g zeolite-hr.) was obtained in a fluidized bed reactor with chabazite as the carrier. Although this rate is in the high range of reported values for biofilm reactors, desorption experiments proved that nitrification will be the process's rate limiting step, rather than the desorption rate when regenerant solutions as low as 2,440 mg/L Na^+ were used. Separate mode bioextraction of chabazite zeolite with regenerant recycle and sodium bicarbonate buffer for nitrification was investigated [68]. They reported ammonium extraction rates of 0.21 g NH_4^+/L-hour which were limited by the supply of oxygen and equivalent to equivalent to 0.36 mg NH_4^+-N/g zeolite-hour in their system. Successful single stage zeolite bioextraction of zeolite has been reported at temperatures as low as 6°C, and addition of sodium carbonate and sodium bicarbonate was been used to supplement alkalinity and prevent pH decline which would be inhibitory to biological nitrification [64]. High ammonium levels may build up in the bioextraction reservoir of the fill and drain separate stage bioextraction system. High ammonium may inhibit nitrification. Coupling of bioextraction reservoir with the nutrient reservoir for *Solanum tuberosum* cultivation may be an approach to ameliorate excessive ammonium buildup in the bioextraction reservoir.

In the experiments with direct cultivation of *Solanum lycopersicum* with zeolite bioextraction, nitrogen release occurred in consort with plant uptake. Substantial nitrogen release occurred over 93 days with NO_3^- depletion in nutrient reservoirs at ~11 weeks in some cases [62]. Separate stage bioextraction enables optimizations that are free of plant growth requirements, such as seeding of spent IX media with

nitrifying bacterial cultures and alkalinity supplementation. For an optimized separate stage bioextraction process, the time scale for complete ammonium ion removal from spent zeolite through oxidation desorption can be estimated as 6 to 12 weeks. A technological nitrogen capture system could employ alternating operation of two parallel IX treatment trains, with one IX train in treatment mode (i.e. receiving ABR effluent and capturing wastewater N) and the second IX train in regeneration mode (i.e. fill and drain bioextraction). An IX design with an 8 month nitrogen capture capacity (single treatment train) would enable bioextraction of spent zeolite in the second IX train well within the time to IX exhaustion.

Hydroponic Potato Cultivation There is substantial interest in potato cultivation with controlled growth including hydroponic systems. Hydroponic systems that apply controlled growth using nutrient solution feeding appear to offer significant advantages for potato production. Hydroponic concepts can draw upon to develop systems that grow potato with wastewater nitrogen recovered on zeolites, particularly for variant of fill and drain cultivation. Hydroponic systems offers higher areal yields and less space than conventional agriculture, large potential reductions in consumptive water use, high efficiency of nutrient use, faster growth and lower cultivation times [69]. Controlled growth using nutrient solution feeding appears to offer significant advantages for potato production. Greater potato productivity and high tuber quality with hydroponically grown seed tubers was reported versus those planted in porous substrate; higher efficiency of water use and greater mineral nutritional control were also advantages of hydroponic culture [70]. Hydroponic systems have the potential of discriminating nutrient control, as for example in the delineation of the interactions and effects and of nitrogen and potassium ions in nutrient growth solutions on the yield, dry matter content, and number of tubers of hydroponically grown potatoes [71]. Potato production (*Solanum tuberosum L.*) is among the most responsive of crop species to nitrogen application and controlled growth environments provide a means to optimize nitrogen supply and increase productivity [72].

The system for potato cultivation with recovered wastewater nitrogen offers some of the advantages of hydroponic systems by intensifying productivity and reducing the arable land area required [73]. Fill and drain cultivation of *Solanum tuberosum* provides some of the advantages that hydroponic systems have over field soil agriculture [74]. Additionally, the system is provides a resilient method to reduces the overreliance on rain-fed agriculture and vulnerability to climate change that are emblematic of regions in the developing world [75]. The system is intended to achieve high productivity with locally sourced nitrogen, albeit with far less critical complexity than might be found with many hydroponic growth systems.

Summary Nitrogen on granular zeolite can be incorporated into potato by bioextracting ammonium from the zeolite and supplying ammonium or nitrate for plant cultivation. One and two stage systems are envisioned with different advantages, degrees of complexity and opportunities for optimization. A system for wastewater nitrogen recovery and plant growth is an appropriate technology for sustainable intensification of *Solanum tuberosum* production at local scale. In addition to the nitrogen content, wastewater sources can provide other growth nutrients and supply consumptive water demand for *Solanum tuberosum* production. The potato growth system described in the following section includes a storage feature for bulk treated wastewater.

5. Potato production system

A formulaic design is developed for a system to recover nitrogen from wastewater by sorption on zeolite and to supply captured nitrogen for *Solanum tuberosum*

production. The system extracts nitrogen from wastewater to provide a reliable and flexible nitrogen supply for potato cultivation on an as needed basis, while producing a quality treated wastewater for consumptive demand, harvesting of other constituents, and reuse.

The nitrogen recovery and recycle system:

- Uses a reliable locally generated nitrogen source
- Provide for continuous wastewater processing
- Provide high quality wastewater effluent for reuse
- Recovers and stores nitrogen
- Equalizes nitrogen supply on daily to seasonal time scales
- Provides nitrogen to *Solanum tuberosum* on as as-needed basis
- Provides transmission barriers between wastewater and *Solanum tuberosum production*
- Maximizes efficiency of nitrogen transfer from wastewater to plant biomass
- Limits nitrogen loss to groundwater as nitrate (NO_3^-)
- Limits nitrogen loss to the atmosphere as ammonia (NH_3)

Basis of System A design of the nitrogen capture and *potato* production system is based on 10 people and the nitrogen contained in their waste (**Table 7**). The per capita nitrogen excretion rate is estimated as 12.8/cap-day of which 95% can be recovered by IX. Water usage rates depend on available water sources. Higher per capita water use rates dilute waste components and reduce the nitrogen concentration (**Figure 8**). The wastewater nitrogen concentration is 128 mg/L at a design flowrate of 100 liters per capita per day, a water use rate established by the World Health Organization that ensures that most basic human needs are met and few health concerns arise [77]. The system provides the sanitation waste of 10 people to provide 44.4 kg/yr. of nitrogen for potato production.

Optimization of potato production with the controlled growth system provide advantages over non-controlled cultivation. The system design considers an aerial tuber production rate of 30 t/ha-yr. to be achievable, which is well below the reported tuber productivities of 50 t/ha-yr. and greater for high input production systems [3] and 157 t/ha-yr. in hydroponic systems [74]. If higher areal productivities can be achieved, which is quite possible, the main effect on the system architecture would be smaller area of cultivation. The nitrogen content of potato tubers is reported to increase with increasing nitrogen availability, plateauing at 1.53%, while nitrogen content of foliage was twice as high as tubers [8]. A potato tuber content of 1.53% was used in the basis of system design (**Table 7**). Tuber biomass is reported to constitute ca. 80% of total plant mass for *Ants* and *Vigri* potato varieties at growth maturity [78]. It is maintained, however, that 60% of nitrogen uptake by *Solanum tuberosum* occurs before tubularization [30]. The nitrogen use efficiency (NUE) has been defined as the tuber dry matter yield per unit of applied nitrogen [76]. For the purpose of a tuber yield calculation, a nitrogen use efficiency (NUE) of 33.3% was estimated from these reports for *Solanum tuberosum* tuber production

System Basis	
# people	10
g N/cap-day	12.8
g COD/cap-day	154
Per capita flow, L/cap-day	100
N cone., mg/L	128
COD cone., mg/L	1,540
% N capture	95
kg N/yr	44.4
tuber yield, t/ha-yr	30
tuber N content, %	1.53
NUE, %[1]	33.3
Areal N supply, g/m^2-yr	138
Cultivation Area, m^2	322
ha	0.0322
Tuber production, t/yr	0.967
Per capita yield, kg/cap-yr	96.7

[1]*Nitrogen Utiliztion Efficiency [76].*

Table 7.
Formulaic design for Solanum tuberosum growth on wastewater nitrogen: System basis.

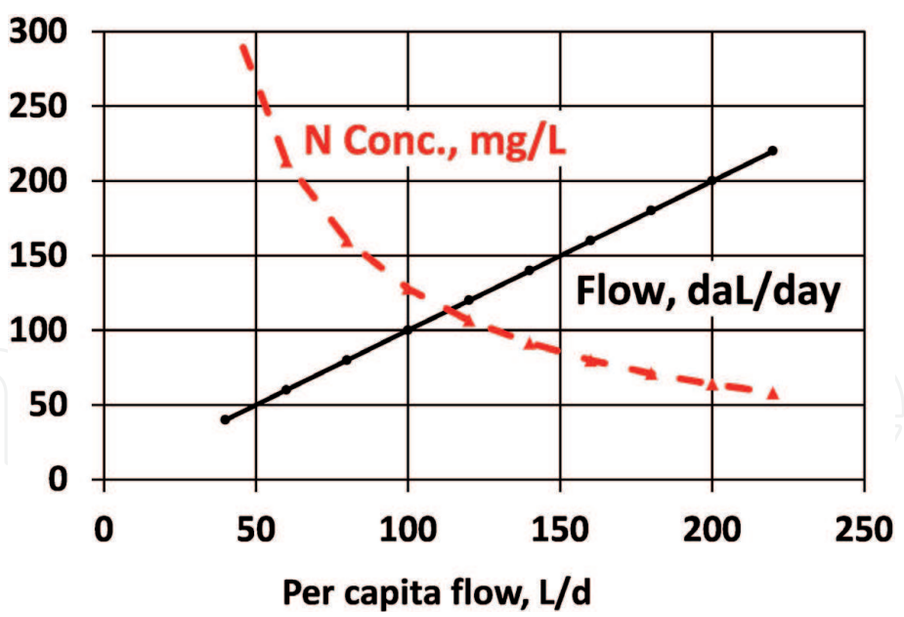

Figure 8.
Water use and wastewater nitrogen concentration.

from supplied nitrogen. An aerial nitrogen supply of 138 g/m^2-yr to 322 m^2 produces 967 kg/yr. potato tubers, a yield of 97 kg/cap-year. The system provides the high areal productivity that is central to increasing potato production in many low income areas dominated by small scale farmers [79].

System Components A schematic of system for nitrogen capture from wastewater, bioextraction of nitrogen from zeolite, and *Solanum tuberosum* production is shown in **Figure 9**. Components of the system are listed in **Table 8**. The wastewater flow

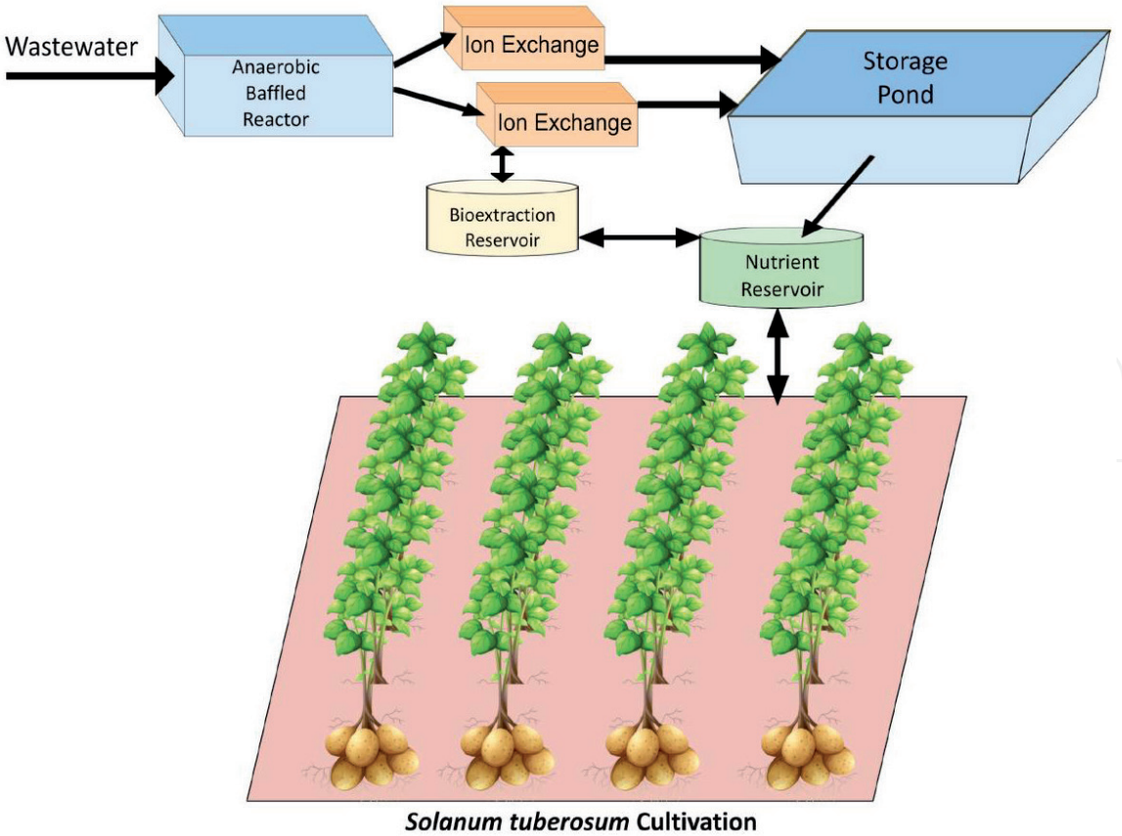

Figure 9.
System schematic.

Component	Configuration	Function	Mechanisms	Flow Regime
Anaerobic Baffled Reactor (ABR)	Series Upflow Chambers	Pre-treatment for IX Reduce suspended & colloidal solids, Ammonification	Sedimentation Filtration Hydrolysis Anaerobic treatment	Continuous flow as wastewater is generated
Ion Exchange (IX) (2 parallel modules)	Series Media Chambers	NH_4^+ sequestration NH_4^+ bioextraction	Flow through porous media Oxygenation of IX media Nitrification	Loading mode: Continuous flow Extraction mode: Fill and Drain
Storage Pond (SP)	Open Pond	Storage of IX effluent	Retention	Continuous flow
Bioextraction Reservoir (BR)	In-ground Tank	Bioextraction of NH_4^+ from IX Media	Oxygenation of IX media Nitrification Accumulation of extracted nitrogen	Fill and Drain
Solanum tuberosum **Cultivation (SC)**	Subsectioned Growth Plots	Receive nutrient solution from NR	Solarium tuberosum Growth	Fill and Drain Mode Irrigation Mode
Nutrient Reservoir (NR)	In-ground Tank	Supply nutrient solution to SC	Nutrient and water supply to SC	Fill and Dram Mode Irrigation Mode

Table 8.
System components: Solanum tuberosum growth on wastewater nitrogen.

path is into the Anaerobic Baffled Reactor (ABR), through Ion Exchange (IX), and into the storage pond (SP). Wastewater passes through this system at the rate at which it is generated. ABR provides pre-treatment for IX by reducing suspended and colloidal solids and oxygen demand. There are two parallel IX modules that each alternate between nitrogen recovery mode and regeneration mode, with each IX module in the opposite mode as the other.

In nitrogen recovery mode, IX media is saturated, preventing oxygen ingress and maintaining anaerobic conditions for which ion exchange retention of NH_4^+ is highly effective [38]. IX receives ABR effluent, extracts NH_4^+, and passes treated wastewater to the storage pond. One IX module is sized to provide an eight month NH_4^+ recovery capacity, providing sufficient time for regeneration of the other IX module. For regeneration, a Bioextraction Reservoir (BR) is placed below ground for passive drainage from IX. In regeneration mode, IX media is saturated in the *fill stage* and unsaturated in *drain stage*, enabling oxygen ingress for nitrification and desorption. The Bioextraction Reservoir (BR) is pumped to saturate the IX media with gravity return flow (fill and drain). Bioextraction results in a buildup in BR of NH_4^+ and NO_3^-. The storage pond received effluent and serves to augment consumptive water use, supply other nutrients, and for other beneficial reuses. The potato production system is the 322 m^2 area of *Solanum tuberosum* Cultivation (SC) and the coupled Nutrient Reservoir (NR) that receives nutrient solution from BR. NR supplies SC with nutrient water and receives drainage from SC. NR/SC operates in either fill and drain mode or irrigation mode. In fill and drain mode, SC media are periodically saturated and then drained; media have high porosity and hydraulic conductivity. During the drained period, oxygen ingress into unsaturated pore spaces is greater than for the finer grained soils of conventional soil-based agriculture. In irrigation mode, SC media are more conventional soils with lower porosity and hydraulic conductivity, with appropriate irrigation schedules.

Anaerobic Baffle Reactor The Anaerobic Baffle Reactor (ABR) has been used for passive, low maintenance primary treatment of sanitation water in low income communities [57]. The ABR is readily constructed and suitable for the nitrogen recycle system. The features of the ABR in the system design are listed in **Table 9**. The three chamber ABR provides a 10 day Hydraulic Residence Time (HRT) and low COD

Anaerobic Baffled Reactor	
Continuous flow through	
HRT, day	10
Liquid volume, m^3	10
COD Loading, kg/m^3-day	0.154
Chambers	
#	3
W × L × D, m	1.5 × 2.0 × 1.11
headspace height, m	0.4
total depth, m	1.51
mean upflow velocity, cm/hr	1.4
Total ABR	
W × L × D, m	1.5 × 6.0 × 1.51

Table 9.
System design: Anaerobic baffled reactor.

loading (0.15 kg/m^3-day) typical of onsite treatment of sanitation waste in anaerobic upflow reactors [60, 80]. Anaerobic treatment of organic wastes produces methane (biogas), which could be harvested from the ABR system. Biogas a local source of energy that can be used as fuel for cooking or lighting for example.

Ion Exchange and Bioextraction Reservoir The salient features of the ion exchange and bioextraction components of the system design are listed in **Table 10**. The two

Ion Exchange Module (2 parallel units)	
Continuous flow through	
Clioptilolite media	
Longevity, mouths	8
Effective CEC, meq/g	0.925
Mass, kg	2,285
Bulk density, kg/m^3	800
Volume, in^3	2.86
IX chambers	
#	4
volume, m^3	0.71
W × L × D, m	0.8 × 0.8 × 1.12
total depth, m	1.70
mean upflow velocity, cm/hr	6.5
Total IX (single module)	
W × L × D, m	0.8 × 3.2 × 1.7
Porewater volume, m^3	1.43
Bioextraction Reservoir	
Fill and draw	
volume, m^3	3.0
diameter, m	2.0
depth, m	0.96
Fill event	
events/day	6
event time increment, hr	4
pump on period, min	15
pump flowrate, L/m	150
total pumped volume, L	2,250
# porewater volumes	1.58
Storage Pond	
days storage	45
volume, m^3	45
area, m^2	49.0
depth, m	0.92

Table 10.
System design: Ion exchange modules (2 parallel units) & storage pond.

parallel IX modules are included (**Figure 9**). The IX modules are identical, each with four chambers containing 0.71 m^3 zeolite. The two IX modules operate alternately, with one in sorption mode receiving ABR effluent while the second is in regeneration mode. The zeolite in each module provides a longevity of eight months for nitrogen recovery (**Table 10**). The eight month design provides substantial storage of the nitrogen load and regeneration time in the alternate IX. When the NH_4^+ capacity of the IX module in the sorption mode approaches exhaustion, each IX module is switched to the alternate function.

When IX modules are each switched to the alternate function, regeneration of spent zeolite is initiated in the IX module that has just been switched from sorption mode. Regeneration is accomplished in fill and drain mode and is conceptually similar to one stage bioregeneration that shown in **Figure 5** without the plant growth. The Bioextraction Reservoir (BR) is pumped to the IX chambers in fill stage, which then passively drains back to BR after pumping ceases (*drain stage*). The duration and rate of pumping determines oxygen supply to nitrifiers on the zeolite surfaces and NH_4^+ and NO_3^- levels in pore water or film water on the zeolite media. The fill and drain schedule in **Table 10** shows six events per day in which IX media if fully saturated; adjustment to this schedule can readily be made during system operation. The time scale for complete ammonium ion removal from spent zeolite through oxidation desorption can be estimated as 6 to 12 weeks for an optimized bioextraction process. As bioextraction of zeolite proceeds, NH_4^+ and NO_3^- levels will build up in BR, and transfer of BR content to the *Solanum tuberosum Production* system will consume the BR nitrogen (**Figure 9**).

IX effluent is low in TSS, organic oxygen demand (COD) and carbonaceous biochemical oxygen demand (C-BOD), comparable to a well-treated wastewater effluent [35, 62]. IX effluent is directed to a storage pond for consumptive water supply, provision of other nutrients, or other reuse needs.

Solanum tuberosum Production The system for potato production includes the *Solanum tuberosum* Cultivation (SC) area and the Nutrient Reservoir (NR), which work as a coupled system (**Figure 9**). Salient design features of SC and NR are listed in **Table 11**. The cultivation area of 322 m^2 is based on the nitrogen supply from 10 people and the nitrogen requirement for tuber production at 30 t/ha-yr. (**Table 7**). NR serves as source of nutrient solution by pumping from NR to SC. NR is placed below ground for passive return drainage from SC. NR nutrient solution is managed based on the metabolic needs of *Solanum tuberosum* plants. NR receives nitrogen solution from BR on the basis of nitrogen supply needs and receives SP water on the basis of consumptive water demand and the need for other nutrients.

SC is subsectioned into twelve 26.8 m^2 plots with 42 cm media depth to accommodate potato root depth. Two manners of *Solanum tuberosum* cultivation are considered: fill and drain mode and irrigation mode (**Table 11**). Either mode enables careful control of the magnitude and timing of nitrogen and water supply to optimize *Solanum tuberosum* growth, maximize the fraction of nitrogen transferred from wastewater to nutrient reservoir to plant biomass, and limits nitrogen losses to groundwater and atmosphere. The potato has a shallow root system and significant yield response to frequent irrigation. The two growth system presented in **Table 11** provide water application rates that enable intensification of the potato yield in small areas.

The fill and drain mode of potato cultivation is similar to architecture one stage bioregeneration shown in **Figure 5**. SC media are periodically saturated and then drained, with growth media of relatively high porosity and hydraulic conductivity. The fill and drain frequency is three fill events per day at eight hour interval to each subsection (36 events/day total), where enough NR water is pumped to fully

Solanum tuberosum Cultivation System		
Cultivation		
total area, m^2	322	
# subsections	12	
area, m^2	26.8	
Nutrient Reservoir		
Sequential pumping to subsections		
volume, m^3	2.5	
diameter, m	2.0	
depth, m	0.80	
	Fill and drain mode	**Irrigation mode**
Growth media		
depth, cm	42	42
porosity	0.50	0.40
pore water volume, m^3	5.64	4.51
Subsection pumping event		
# events/day	3	1
total events/day	36	12
event time increment, hr	0.67	2.0
pump on period, min	30	15
pump flowrate, L/min	200	10
total pumped volume, L	6,000	150
water depth applied, cm	22.4	0.56
# porewater volumes	1.06	0.033
water depth applied, cm/day	67.1	0.56
nitrogen conc., mg/L	100	180
nitrogen applied, g/m^2-day	9.6	0.14

Table 11.
System design: Solanum tuberosum *cultivation.*

saturated the growth media. A nitrogen concentration of 100 mg/L in the nutrient solution provides 9.6 g/m^2-day for cultivation, with only a portion used for plant assimilation and the remainder retuning to NR. In irrigation mode, SC media are more conventional soils with lower porosity and hydraulic conductivity. The irrigation mode schedule is one application per day (12 events per day total) of 0.156 cm depth, providing a nitrogen application of 0.14 g/m^2-day from 180 mg/L nitrogen concentration in NR (**Table 11**). The irrigation schedule would be adjusted through the growth cycle to match the metabolic needs of the potato plant.

Fill and drain mode entails growth in granular, non-cohesive medium and potato prefers naturally loose soils which offer the least resistance to enlargement of the tubers [81]. It can be speculated that fill and drain cultivation of potato may be superior to irrigation mode in flushing or breaking down of potato pathogens, or in limiting their accumulation. Fill and drain and irrigation mode cultivation can both incorporate ridging (earthing up) of growth media, which is advantageous for pest control [81].

Summary A system is presented to capture nitrogen from locally generated wastewater and recycle it into potato production. Nitrogen is recovered and provided for *Solanum tuberosum* production on as as-needed basis. The system efficiently transfers nitrogen from wastewater to plant biomass and limits nitrogen losses to groundwater and atmosphere. Physical separation of wastewater treatment and *Solanum tuberosum* cultivation provides a barrier to transmission of pathogens. The nitrogen recycle system is an appropriate technology for sustainable intensification of *Solanum tuberosum* production at local scale. Projected tuber yields are 967 kg/year on a 322 m^2 plot (10 person basis). The nutritional productivity of this system can be estimated as 92.5 kg/year of crude protein [82].

Use of local wastewater nitrogen can increase *Solanum tuberosum* production and contribute to a reliable world food supply. The nitrogen recycle system meets the development goals of sustainable intensive farming, including use of local of resources to close the yield gap, reduction of footprint, and reduction of wastes [83, 84]. An alternative deployment of the nitrogen recycle system is for intensive breeding of potato seedlings to plant on adjacent areas. Potato crop is usually grown from seed potatoes, small tubers or pieces of tuber sown to a depth of 5 to 10 cm [2]. Potato seedling can be a price barrier, for example comprising 40 to 60% of the total potato production cost to smallholder farmers in African countries [79]. Dedicating the nitrogen system to seed production would focus its more intensive operation on a significant component in the price chain. Other adaptions of the nitrogen recovery and potato growth system are enclosed growth cultivation and agroforestry.

6. Summary and path forward

Local scale *Solanum tuberosum* cultivation has the potential to contribute to food security in low-income and developing countries. This chapter proposes to grow *Solanum tuberosum* using nitrogen captured from wastewater, providing a reliable and low cost nutrient supply that is available in urban, peri-urban and rural areas. A multi-element production system is envisaged that optimizes the functions of primary wastewater treatment (anaerobic upflow solids blanket), ammonium (NH_4^+) capture (anaerobic ion exchange), ammonium release (aerobic bioextraction), and *Solanum tuberosum* cultivation (fill-and-drain hydroponics and irrigation). Key to ammonium capture is the use of natural, low cost ion exchange zeolites which are available worldwide. The architecture of the system separates capture of nitrogen from nitrogen release and delivery, enabling the quantity and timing of nitrogen delivery to match the metabolic needs of *Solanum tuberosum* growth. Potential potato yields of 967 kg/year on a 322 m^2 plot (10 person basis) make the system an appropriate technology for sustainable intensification of *Solanum tuberosum* production at local scale.

This chapter provides the conceptual framework of a system focused on supplying nitrogen for *Solanum tuberosum* growth. The technique can be adapted or interfaced with other processes to provide additional growth needs including water and other nutrients. The intent of the chapter is to stimulate inventive thought and facilitate innovation, demonstration and adoption. Design and testing of field systems is needed to develop process knowledge and skill. Partnerships of environmental/sanitary engineers and agronomists would provide the most fruitful collaborative expertise. Funding from NGOs, non-profits or governments can accelerate the path forward and bring the benefits to realization.

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