Supplementary materials related to the publication:

# D'ostuni, M., Stanghellini, C., Boedijn, A., Zaffi, L., Pennisi, G., & Orsini, F. (2023). Evaluating the impacts of nutrients recovery from urine wastewater in Building-Integrated Agriculture. A test case study in Amsterdam. *Sustainable Cities and Society*, 91, 104449.

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**Abstract:** Recent studies concerning the integration of agricultural practices in cities demonstrated that Urban Agriculture (UA) can boost new sustainable urban developments. New technologies allow to integrate soil-less cultivation in- and on- mixed-use buildings, creating new synergies between the built environment and the urban food system. Accordingly, resource flows from buildings are an untapped opportunity for the creation of circular urban metabolisms that rely on recycling waste as input for food production systems. On this trail, this research work focuses on evaluating the feasibility of using urine and greywater streams as nutrient solution in a theoretical model of Building-Integrated Agriculture (BIA) located in Amsterdam. Results showed that it is feasible to use urine and greywater as nutrient solutions (NS). However, treated urine showed higher concentration of macronutrients compared to fertilizer recipes found in literature, and therefore needed to be diluted with increasing amount of greywater to match either N or P concentration. Accordingly, P deficiencies in the plants or excessive N concentration were found in the final wastewater-based NS. Future research is highly recommended to assess the quality of plants grown in BIA systems as well as the possible content of harmful viruses and bacteria in the harvested produce.

**Keywords:** nutrients recovery; green buildings; building-integrated agriculture; indoor food production; wastwater

**Supplementary material (SM)**

The supplementary material linked with the paper "**Evaluating the impacts of nutrients recovery from urine wastewater in Building-Integrated Agriculture. A test case study in Amsterdam**" aims at showing most of the calculation that brought to the conclusions of the paper as well as some more explanatory figures that couldn't fit the text. Most of the calculations were done on excel sheets that are here reported with, whenever possible, an associated description.

SM *section 2.6*

To make it clearer to the reader what are the differences between hydroponic greenhouses and vertical farms we provided figures and schemes that visually identify the two systems (**Figure 1a**; **Figure 1b**):

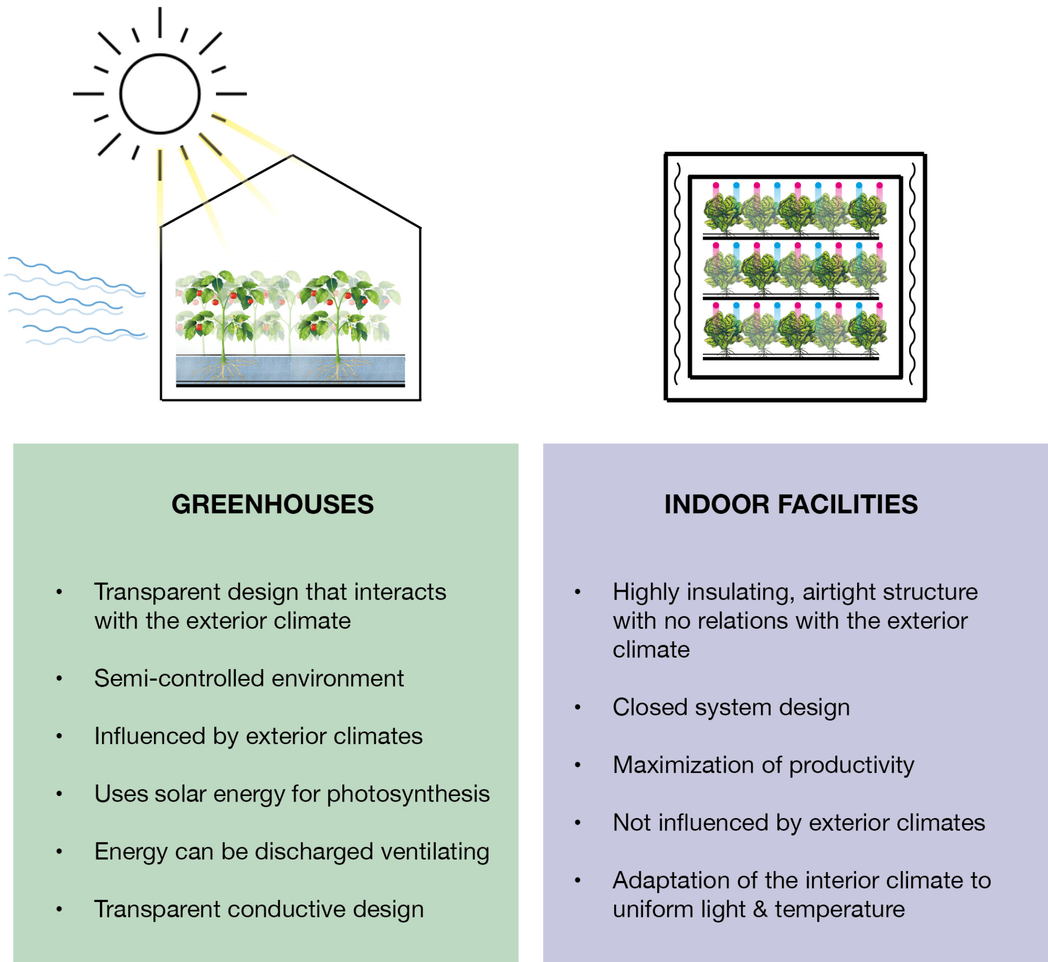
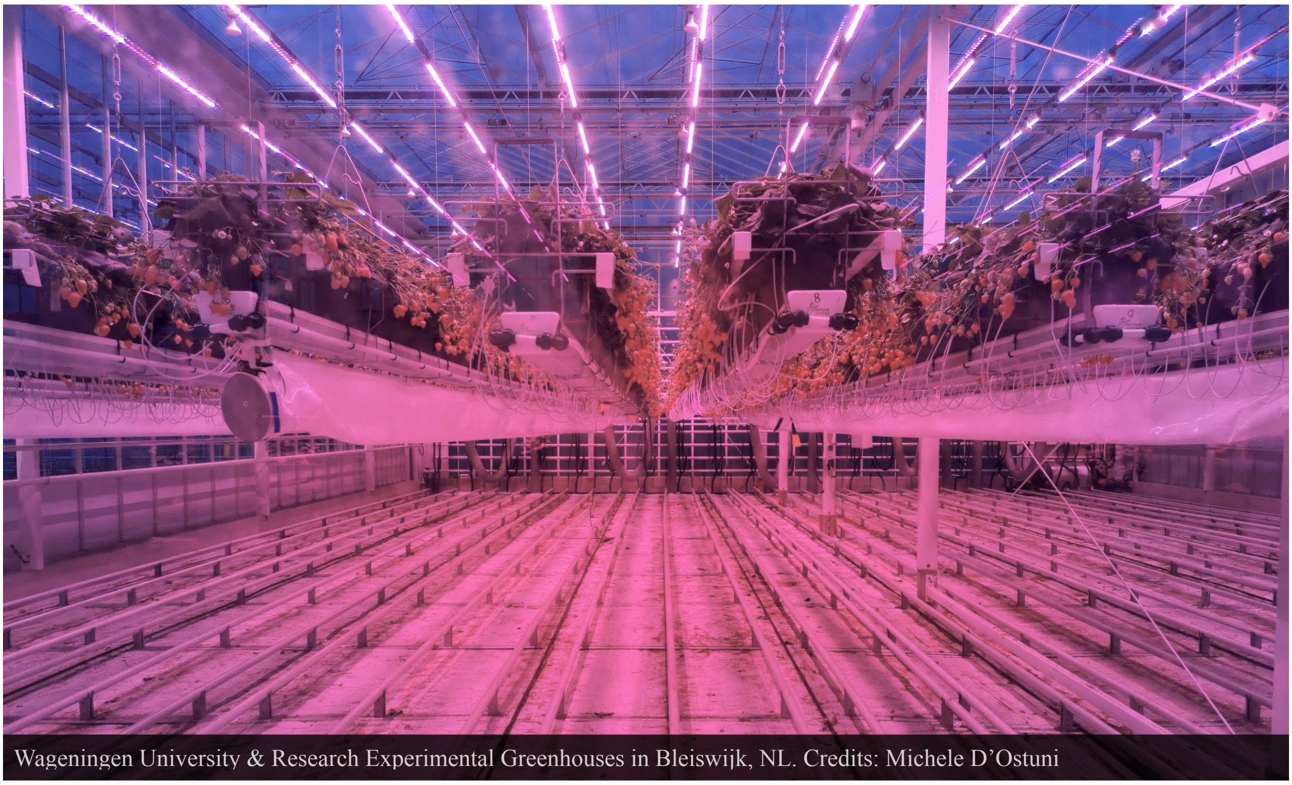



**Fig. 1a: Differences between Greenhouses and Indoor Facilities**



Wageningen University & Research Experimental Greenhouses in Bleiswijk, NL. Credits: Michele D'Ostuni

Alma VFarm, University of Bologna, IT. Credits: Marco Raccicchini

**Fig. 1b: Realized examples of an hydroponic greenhouse (A) and a Vertical Farm (B)**

SM *section 3.3*

To treat the whole volume of urine coming from the building blocks, it was decided to design two reactors. This has the advantage of keeping the system always working even in case one needs cleaning or repairing. The two MBBR reactors are scaled based on the total ammonium load of the Cluster. As written in Table 9, the total daily load of $NH4^{+}$ is 7740 g/day. Estimating a nitrification rate of ammonium of min 400 - max 800 mg/L (Etter and Udders, 2015), it is possible to calculate the total volume of the two MBBR reactors (See calculation below). After calculations, it resulted that the minimum volume for the reactors at the minimum nitrification rate is 19,4 $m^3$. Thus, to completely treat all nutrients from Cluster 2, two reactors of 9,7 $m^3$ are needed. Depending from the height of the nitrification room, it is possible to assess the spatial footprint of the two reactors. Considering that all ground floors in the Sluisbuurt neighborhood are at least 3,5 meters height, the column height of the reactor could be up to 3,0 m. Thus, if the reactors are positioned in the ground floor of one building, each would need a diameter of 2 m. To each reactor is associated a setting tank where the sludge coming from the nitrification process is collected and then either discharged or recirculated back into the nitrification reactors.

Using Vuna final report 2015 conclusion on nitrifying MBBR reactor to turn the ammonia in urine into a stabilized ammo-nitrate (fertilizer), we have compared sizing of the reactor using conventional Nitrifying MBBR design in waste water treatment industry. We found similar reactor volumes (20.6 m3 vs 19 m3). However, wastewater industry is aiming to treat most of ammonia, whereas the Vuna project is mostly interested in converting half of the ammonia load into nitrate, to form a stabilized ammo-nitrate fertilizer at pH around 6.5. The comparison was however helpful to gain confidence in sizing of the nitrifying column for this theoretical design (based on a realized reactor). **In conclusion, to treat 860 residents worth urine into ammo-nitrate fertilizer, we would need two reactors of 3 m high and 2 m diameter**

Results are shown in the following **Table 1** and graphically summarized in **Figure 2**:

Table 1: Sizing the MBBR reactor and comparing it with the MBBR reactor realized in the VUNA project (Etter and Udert, 2015)

| Nitrifying MBBR (Moving bed biological reactor) | | | |
|---|---|---|---|
| **Key Design parameters** | **value** | **unit** | **typical ranges** |
| **1- Basis for design (flows and loads):** | | | |
| Number of people covered in treatment work | 860 | person | |
| Specific urine collected per person per day | 1,4 | l/per/day | |
| Urine volume to be treated per day | 1204 | l/day | |
| Average continuous flow of urine | 0,050 | m3/h | |
| Urine Ammonia load | 7740 | g NH3-N/day | |
| Urine BOD load | 3405 | g BOD/day | |
| Urine BOD load | 3,4 | kg BOD/day | |
| **2- Reactor design volume according to Thames Water Asset standard AM-DES-WWT-WWT 4.6b (IFAS dec 2017):** | | | |
| Specific protected surface area of media | 800 | m2/m3 | 150 - 1200 for plastic media<br>4000 - 7000 for porous media |
| Max organic surface loading rate | 10 | g BOD/m2/day | 10-13 (@25oC) |
| Max F/M ratio | 0,15 | kg BOD/kg MLSS/day | 0.15 - 0.20 |
| MLSS Concentration | 2500 | kg MLSS/m3 | 2000 - 3500 |
| Min Retention time | 2,5 | h | 2h - 5h |
| Biomedia filling fraction | 67 | % | 50 - 67 |
| Maximum media ammonia loading rate | 0,7 | g NH3-N/m2/day | |
| Surface Media required for nitrification | 11057 | m2 | |
| Min Volume media required for nitrification | 13,8 | m3 | |
| Min volume required to maintain RT | 0,13 | m3 | |
| Min volume required to allow for media expansion | 20,6 | m3 | |
| **Conclusion: nitrifying reactor volume required** | **20,6** | **m3** | |
| **3- Reactor design volume according to eThekwini pilot plant (Etter and Udert, 2015):** | | | |
| Urine Ammonia concentration | 1800 | mgN/l | |
| urine volumetric flow | 50 | l/day | |
| Assumed volume urine per person per day | 1 | l/p/day | |
| Number of people urine equivalent | 50 | persons | |
| Urine ammonia load | 90 | gNH3-N/day | |
| max nitrification rate | 800 | mgN/l/day | |
| Min nitrification rate | 400 | mgN/l/day | |
| minimum reactor volume @ max nit. rate | 112,5 | liters | |
| **minimum reactor volume @ min nit. rate** | **225** | **liters** | |
| Infered specific Reactor volume design parameters 1: | 5 | liter/person | |
| Infered specific Reactor volume design parameters 2: | 2,5 | liter/(gN/day) | |
| Volume reactor design parameter 1 | 4 | m3 | |
| Volume reactor design parameter 2 | 19,35 | m3 | |
| **Conclusion: Total nitrifying reactor volume required** | **19,4** | **m3** | |
| **Dimension for 2 reactors:** | | | |
| **assumed column height** | **3,0** | **m** | |
| **diameter internal column** | **2,0** | **m** | |
| **Number of reactors:** | **2** | | |

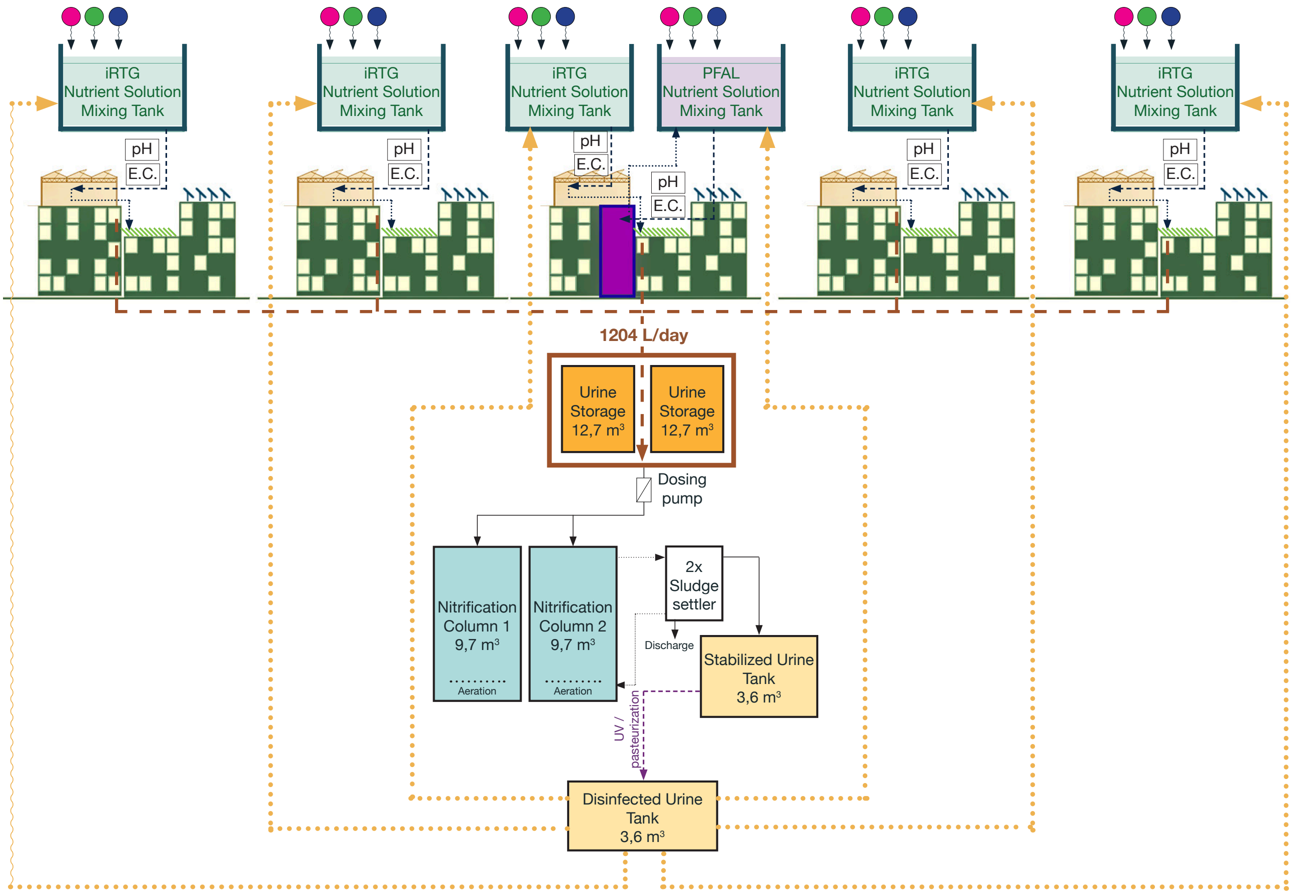



**Figure 2: Nitrification treatment for urine in Cluster 2 - Flow concept**

SM *Section 3.3.1*

Calculating the nutrient concentration in the wastewater-based fertilizer after the pre-treatments (nitrification for urine and green wall for greywater) it was clear that the didn't match at all the common commercial fertilizer recipe used in the nutrient solution to feed the crops as shown in **Table 3** in the text.

In this regard, nutrient concentration should be reduced to match commercial fertilizer recipes. The solution adopted in the paper consisted in reducing the amount of treated urine in the nutrient solution to further dilute the mixture, lowering the concentration of N, P, and K. Since both N and P are in a higher concentration in the wastewater-based fertilizer, we could either dilute the solution to match P or N concentrations as shown here in **Table 2a** and **Table 2b**.

Table 2a: Wastewater-based fertilizer dilution to match P concentration of commercial fertilizer

| ***1- Nutritive solution specifications*** | | **Leafy Green** | | **Fruit vegetable** | | |
|---|---|---|---|---|---|---|
| water requirement | l/day | 2365 | | 5456 | | |
| N concentration | mg/l | 173,6 | | 295,4 | | |
| **P concentration** | **mg/l** | **34,1** | | **48,4** | | |
| K concentration | mg/l | 281 | | 421 | | |
| N requirement | g/day | 411 | | 1612 | | |
| P requirement | g/day | 81 | | 264 | | |
| K requirement | g/day | 665 | | 2297 | | |
| *2- Available solutions:* | | | | | | |
| Stabilized urine | | | | | | |
| Volume available | l/day | 1204 | | 1204 | | |
| N concentration | mg/l | 6429 | | 6429 | | |
| P concentration | mg/l | 571 | | 571 | | |
| K concentration | mg/l | 2000 | | 2000 | | |
| Mass N available | g/day | 7740 | | 7740 | | |
| Mass P available | g/day | 688 | | 688 | | |
| Mass K available | g/day | 2408 | | 2408 | | |
| | | | | | | |
| Grey water | | | | | | |
| Volume available | l/day | 75673 | | 75673 | | |
| N concentration | mg/l | 12 | | 12 | | |
| P concentration | mg/l | 4 | | 4 | | |
| K concentration | mg/l | 8 | | 8 | | |
| *3- Nutritive solutions prepared from urine and grey water* | | | | | *Total* | *used (%)* |
| **Volume urine** | **l/day** | **126** | | **429** | **555** | **46%** |
| Volume grey water | l/day | 2239 | | 5027 | | |
| Total volume made | l/day | 2365 | | 5456 | | |
| N concentration | mg/l | 354 | | 516 | | |
| **P concentration** | **mg/l** | **34** | | **48** | | |
| K concentration | mg/l | 114 | | 165 | | |

Table 2b: Wastewater-based fertilizer dilution to match N concentration of commercial fertilizer

| *1- Nutritive solution specifications* | | Leafy Green | Fruit vegetable | | |
|---|---|---|---|---|---|
| water requirement | l/day | 2365 | 5456 | | |
| **N concentration** | **mg/l** | **173,6** | **295,4** | | |
| P concentration | mg/l | 34,1 | 48,4 | | |
| K concentration | mg/l | 281 | 421 | | |
| N requirement | g/day | 6 | 14 | | |
| P requirement | g/day | 1 | 2 | | |
| K requirement | g/day | 10 | 20 | | |
| | | | | | |
| **2- Available solutions:** | | | | | |
| **Stabilized urine** | | | | | |
| Volume available | l/day | 1204 | 1204 | | |
| N concentration | mg/l | 6429 | 6429 | | |
| P concentration | mg/l | 571 | 571 | | |
| K concentration | mg/l | 2000 | 2000 | | |
| Mass N available | g/day | 3673 | 3673 | | |
| Mass P available | g/day | 327 | 327 | | |
| Mass K available | g/day | 1143 | 1143 | | |
| | | | | | |
| **Grey water** | | | | | |
| Volume available | l/day | 75673 | 75673 | | |
| N concentration | mg/l | 12 | 12 | | |
| P concentration | mg/l | 4 | 4 | | |
| K concentration | mg/l | 8 | 8 | | |
| | | | | | |
| **3- Nutritive solutions prepared from urine and grey water** | | | | **Total** | **used (%)** |
| Volume urine | l/day | 60 | 240 | **300** | **25%** |
| Volume grey water | l/day | 2305 | 5216 | | |
| Total volume made | l/day | 2365 | 5456 | | |
| **N concentration** | **mg/l** | **175** | **294** | | |
| P concentration | mg/l | 18 | 29 | | |
| K concentration | mg/l | 59 | 96 | | |

SM *Section 3.4*

The system used for greywater treatment referred to the potted green wall design studied and implemented by Prodanovich et al. Here, the potted green wall was composed by a modular structure called Gro Wall 4.5 designed by Atlantis and sold both in Australia and U.K. The structure of the green wall is made by recycled plastic box with an incision made on top of each box that could accommodate the irrigation pipes. Pots are wedged in the plastic structure and filled with 6 L of media mix to allow plants' growth (**Figure 3a**).

**Figure 3a: Potted green wall structure**
Credits: *Gro Wall 4.5 by Atlantis UK* - https://www.gro-wall.co.uk/gro-wall-4-5

The results of the reported study indicates that a system with two pots, positioned one on top of the other, consistently removes pollutants from the greywater (Prodanovich et al., 2020). Due to the minimum dimensions of the system, to cover larger loads of greywater it must be replicated to reach the right size to treat the daily loading rate. Treated water can be collected from each two pots height system and redirected to a single collection tank (**Figure 3b**).

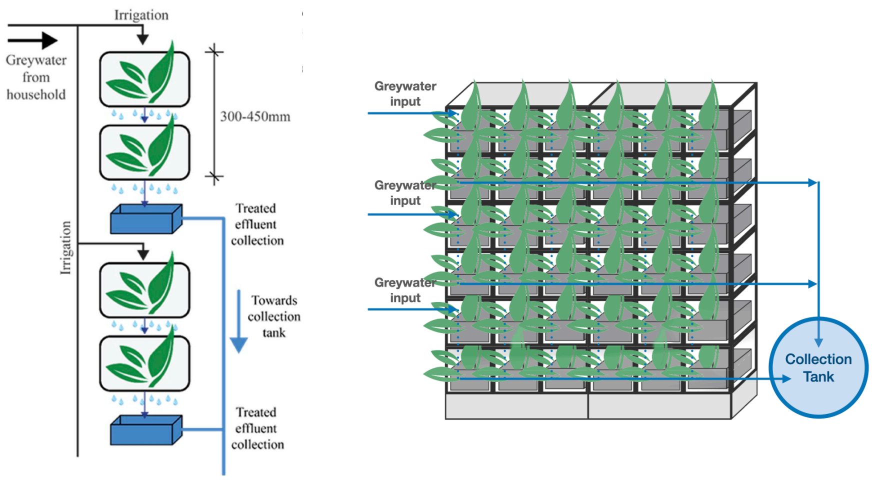



**Figure 3b: Characterization of the POT design Green Wall**
Credits: Prodanovic, V., Hatt, B., Mccarthy, D., Deletic, A. (2020). Green wall height and design optimisation for effective greywater pollution treatment and reuse. *Journal of Environmental Management. V261.* DOI: 10.1016/j.jenvman.2020.110173.

Considering the characteristics of Cluster 2, it is recommended that the total dimension of the green wall would be distributed across the 5 building blocks of the Cluster. This way, the total surface of the green wall can be divided by 5, resulting in five green wall each of 70 $m^2$. Assuming that the maximum height of the building blocks is given and it is 20 meters (Gemeente Amsterdam, 2017), a width of 3.5 meters only on each building block would be required to treat the approximately 15.240 L $day^{-1}$ of greywater (76.196 L $day^{-1}$ / 5). Thus, based on this consideration, the final greywater treatment concept is reported in **Figure 4**.

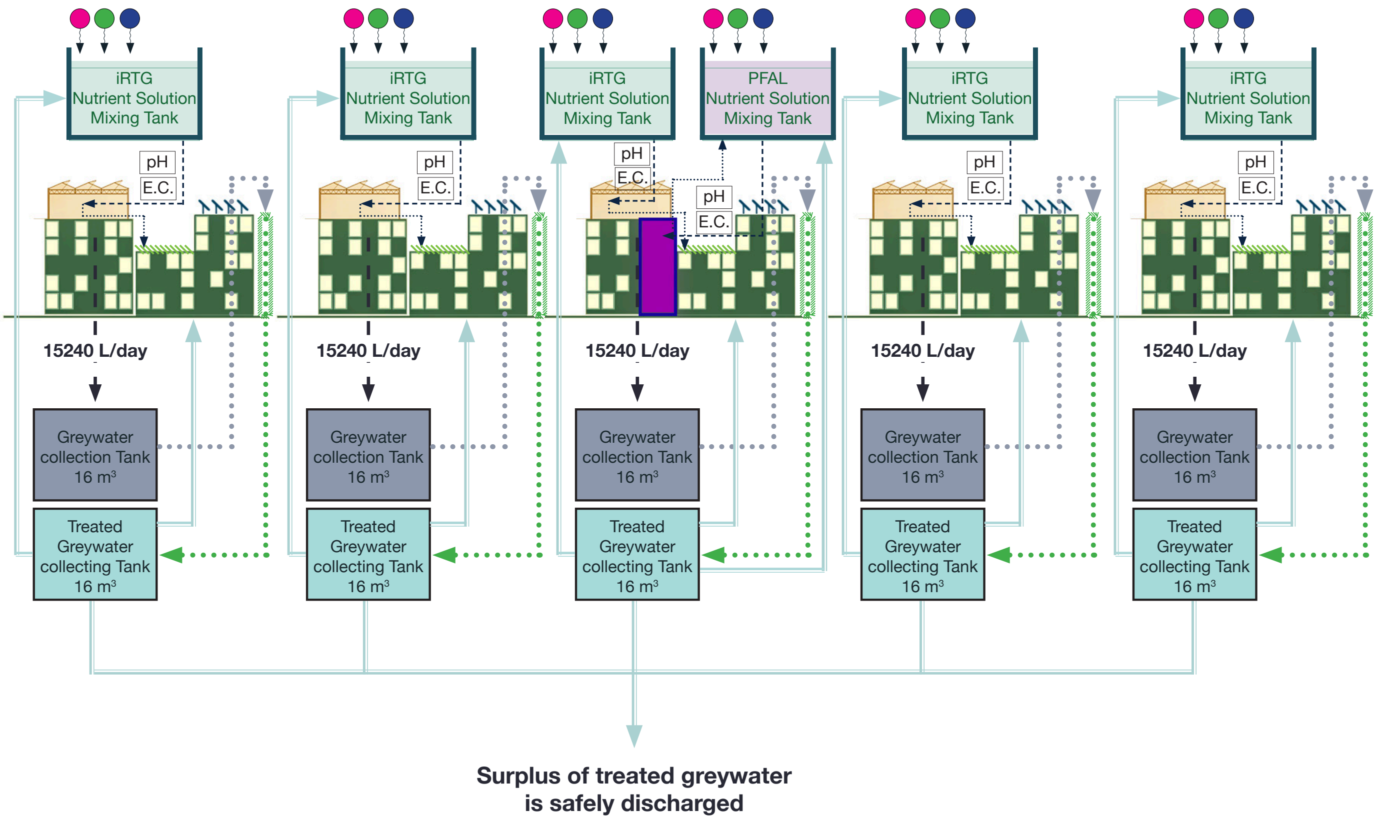



**Figure 4: Green wall greywater treatment for Cluster 2 - Flow concept**

Finally, the whole components of the the BIA cluster needed for wastewater treatment are reported here in **Table 3**.

Tab. 3: Components needed for the wastewater treatment in the Sluisbuurt

| Urine | | Greywater | |
|---|---|---|---|
| **Treatment** | | **Treatment** | |
| Components | Characteristics | Components | Characteristics |
| Urine diverting dry toilets | Allow to collect urine without contamination | 5x collecting water tanks | Collect greywater from each building block |
| 2x Urine storage tanks | Store urine with a retention time of 3 weeks. | 5x mesh filters | Help separate the suspended solids that may clog the system |
| 2x Dosing pumps | Pump the right amount of urine inside the nitrification reactors | 5x Geen walls | 70 m2 each |
| 2x MBBR reactors with integrated sludge settlers | Thanks to the integrated biomass carriers are able to recover all nutrients from urine | | 6.5 L media mix of 1:2 coco coir and 1:2 perlite |
| 1x Stabilized urine tank | Collects the urine after nitrification | | Planted with *Carex appressa* |
| 3x UV disinfection parallel units | Transparent pipes integrated with UV lights for disinfection | | Total double layers pots: 622 per green wall |
| 1x Disinfected urine tank | Collects the disinfected urine | 5x collecting treated greywater tanks | Collect the treated greywater at the bottom of each green wall |
| 1x Dosing hydraulic pump | Pump the disinfected urine rich in nutrient in the nutrient solution mixing tanks | 1x hydraulic pump | Pump the treated greywater in the nutrient solution mixing tanks |
| **Results** | | **Results** | |
| Total dimension of the nitrification room | 110 m² | Total dimension of the green walls | 350 m² |
| Total volume of the urine influent | 1204 L/day | Total volume of the greywater influent | 76916 L/day |
| Reused treated urine | 555 L/day | Reused greywater | 26358 L/day |

**Total discharged treated wastewater: 50487 L/day**

**Final COD concentration in discharged wastewater: 37 mg/L**