Table S1 Supplementary Materials A

Description of NBS Units

The NBS units described in this paper and their attributed numbers (given in brackets) are extracted from the complete list of NBS units given in the introductory paper that presents a framework for addressing circularity challenges in cities with NBS (Langergraber et al., 2021). However, new NBS units are being described and applied to enable more efficient resource recovery in the cities; therefore, also additional NBS units are addressed in this paper and described below – marked as additional (ADD).

TREATMENT WETLAND (NBS 21)

INPUTS

Construction

- Gravel, sand, expanded clay and/or similar filter material
- Organic material (compost or soil) (in some cases, e.g., willow system)
- Impermeable liner
- Piping systems and pumps (siphons)
- Geotextile
- Plants (endemic wetland species)

Type of incoming streams

- Raw domestic wastewater (Medium values COD 750, BOD_5 350, TN 60, TP 15, PO_4-P 10, TSS 400 mg/L)
- Primary treated domestic wastewater (primary treated domestic wastewater has 30-40% initial suspended solids and 60-75% initial BOD (Sperling, 2007))
- Greywater (COD 200-700, BOD_5 100-400, TN 8-30, TP 2-7 mg/L)
- Secondary treated domestic wastewater (BOD_5 20-25, COD 100-125, TSS 35, NH_4-N 10 mg/L)
- Tertiary treated domestic wastewater (BOD_5 20-25, COD 100-125, TSS 35, TP 1-2, TN 10-15 mg/L)

Operation

- Gravity or pumping
- Recycling (internal recycling for denitrification enhancing)
- Planting

Maintenance

- Plant biomass harvesting
- Checking the pumps and pipes
- Replacing pumps (per ca. 5 years)
- Replacing media/substrate (once per ca. 10 years), due to clogging and saturated adsorption material

Connecting supporting units

- Phosphorus precipitation (SU 3)
- Solid-liquid separation unit (SU 7)

OUTPUTS

Type of outgoing streams

- Treated water (quality parameters according to supranational / national legislation + emerging organic contaminants according to the EU watch list and the water directive)
- Evapotranspiration (higher humidity, water loss)
- Biomass production (herbaceous plant, wood biomass)
- Spent substrate/media (after e.g. clogging)

Co-benefits and limitations

- Reclaimed water for groundwater recharge, green areas and urban garden irrigation
- Biodiversity (insects, birds, snakes, wildlife, plants)
- Carbon sequestration in a case of biomass use as construction/furniture material
- Removal of pathogens
- Bio-energy production
- Aesthetic
- Heat-island mitigation

Risks

- Mosquitos (not if designed and operated properly)
- Smell (not if designed and operated properly)
- Methane emission (in case of horizontal flow constructed wetland)
- N_2O emission (in case of horizontal flow constructed wetland)
- Insufficient treatment of nutrients (especially in winter/cold months) for environmental discharge
- Clogging (not if designed and operated properly)

Connecting NBS nits

- Composting NBS unit (NBS 23)
- Anaerobic treatment (NBS 26)
- Soil improvement and conservation (NBS 33)
- Street trees and urban parks (NBS 39–42)

Connecting supporting units

- Phosphorus precipitation (SU 3)
- Activated carbon (SU 9)
- Advanced oxidation (SU 10)

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- Urban Wastewater Directive 91/271/EEC

COMPOSTING (NBS 23)

INPUTS

Construction

- Wooden or plastic or concrete boxes for home-composting
- Impermeable liner and leachate collection pipes
- Air and/or water supply devices
- If central composting – impermeable ground, warehouse, large composting tunnels

Type of incoming streams

- Food waste (kitchen waste, market waste….)
- Solid digestate
- Organic fraction of the municipal solid waste
- Green waste (to be used bulking agent)
- Faecal sludge
- Side streams: air, water
- Worms (for vermicomposting)
- Dry matter >40%

Operation

- Mixing (manual or mechanical)
- Ventilation (passive or active, for vermicomposting relies on worms to mix, aerate and fragment)
- Adding bulking materials (to reach optimal texture and optimal oxygenation)
- Adding water (to achieve humidity level in the range of 40-60%)
- Temperature and humidity monitoring (for vermicomposting: temperature should be closely controlled)
- Monitoring of compost regarding maturity, gases (VOCs, ammonia, methane, carbon dioxide, N_2O, NO) and appropriate C/N ratio (25–30)
- pH to be kept between 5–9 (more stringent for vermicomposting)

- Light should be controlled for vermicomposting
- Monitoring of end product (for central composting unit)

Maintenance

Only for central composting unit

- Biofilters and air ventilation systems maintenance in central composting unit
- Water spaying systems
- Maintenance of monitoring devices (humidity, temperature and oxygen)
- Maintenance of mechanical mixing devices

Connecting NBS units

- Solid waste anaerobic treatment (NBS 26)
- Treatment wetlands (NBS 21)
- Street trees and urban parks (NBS 39–41)

Connecting supporting units

- Solid/liquid separation unit (SU 7)
- Mechanical pre-treatment (shredding and mixing) (ADD)

OUTPUTS

Type of outgoing streams

- Compost (C / N: 50-90% (organic) / P / K) / Vermi-compost
- Polluted air (ammonia and VOCs) to be treated
- Leachate (COD, N) to be treated
- Water vapor
- Worms

Co-benefits and limitations

- Waste heat (extra energy) only for composting
- Pathogens removal only for composting
- Feed production

Risks

- Leachate infiltration and/or runoff
- Smell
- Poor hygienisation (too short or not homogenized thermophilic conditions)
- Methane, ammonia, NO and N_2O emissions
- Too dry or too moist compost
- Energy needed due to bad design or climate conditions
- Presence of microplastic (depending on incoming material quality)
- Presence of emerging organic contaminants
- Accumulation of metals at toxic levels

Connecting NBS units

- Street trees/ urban parks (NBS 39–42)
- Productive gardens, urban farms and orchards (NBS 49, 51)
- Soil improvement and conservation (NBS 33)
- Green roofs and walls (NBS 13–20)
- Aquaculture (worms) (NBS 44)

Connecting supporting units

- Air treatment
- Leachate treatment
- Disinfection unit (SU 5)
- Heat exchanger
- Mechanical processing (i.e. compost sieving)

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SOIL CONSERVATION AND PHYTOMANAGEMENT (NBS 24, 25, 33)

INPUTS

Construction

- Growing substrate (contaminated soils including technosols and mining contaminated soils or naturally metal rich soils including ultramafic soils)
- Plants for phytoextraction (including hyperaccumulating plants)
- Components (e.g. mulch, woodchips, compost, biochar) to enhance soil structure (texture)/organic matter/water holding capacity and plant support
- Irrigation system (temporary irrigation could be needed unless rainfall is adequate until plants grow or in dry season)
- Manage excess water and nutrients e.g., through design of drainage system

Type of incoming streams

- Irrigation water (surface or groundwater, reclaimed water)
- Appropriate plant species and stage of growth
- Appropriate characteristics for mulch, woodchip, biochar and compost (e.g., pH, CEC, organic matter, porosity)
- Organic and mineral fertilizers for biostimulation purposes

- Addition microbial strains for bioaugmentation purposes

Operation

- Soil preparation (tilling type, fertilizer supply)
- Sowing/seedling, mowing (for leguminous species to enhance nitrogen fixation)
- Planting (for phytoremediation) while taking care of plant density and stage of growth
- Harvesting
- Temporary irrigation could be needed unless rainfall is adequate until plants grow or in dry season
- Pest management (e.g. herbicides)
- Gas emission monitoring (e.g. VOCs)

Maintenance

- Checking soil quality
- Regular maintenance of vegetation (remove litter, harvesting, replanting)
- During dry season and at the initial plant growth stage, irrigation required to maintain plants
- Supply of organic and inorganic fertilizers

Connecting NBS units

- Composting (NBS 23)
- Solid waste anaerobic treatment (NBS 26)
- Treatment wetland (NBS 21)

Connecting supporting units

- Biochar production (SU 6)
- Mulch and wood chips production

OUTPUTS

Type of outgoing streams

- Soil improvement (reclaimed soils; improvements of soil physical, chemical and biological characteristics)
- Material recovery and reuse: biomass from contaminated plants (used for bioenergy generation, biochar or composting- supply of soil conditioner, processing to bio-based materials)
- (Hyper)-accumulator plants (Metals bio-ores)
- Nutrient recovery and reuse
- Water vapor via evapotranspiration (higher humidity, water loss)
- Food and feed (use of leguminous and cereal species, edible halophytes for salinized soil, edible yield from food crops used for purposes of soil stabilization, improvement of soil nutrient/water retention/metabolization capabilities)

Co-benefits and limitations

Ecosystem services enhancement

- Water quality improvement / Groundwater quality preservation
- Stormwater management, water infiltration and retention enhancement, flooding reduction
- Habitat improvement – biodiversity increase or preservation (e.g. increase of beneficial soil organisms)

- Carbon sequestration / N fixation (less N requirement in soil, less fertilizers, less emissions)
- Improved nutrient metabolization, retention and plant uptake (reduction of synthetic fertilizer needed in agriculture)
- Soil organic/inorganic contaminants immobilization and/or removal
- Aesthetic
- Erosion prevention
- Climate regulation/cooling
- Soil compaction prevention

Risks

- Insufficient removal rate and yield of soil pollutants (especially in winter/cold months when plants are quiescent)
- Contaminants transfer in the food chain
- Microplastic or other pollutant inputs (e.g. PAHs, potentially toxic elements) from incoming streams
- Overfertilization
- Inappropriate plant species/growth stage selection

Connecting NBS units

- Composting (NBS 23)
- Solid waste anaerobic treatment (NBS 26)

Connecting supporting units

- Biochar production (SU 6)
- Mulch and wood chips production

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BLACK SOLDIER FLY / INSECT FARMING (ADD)

INPUTS

Construction

- Boxes, bins or containers for growth of adult flies (hatchery/nursery)
- Boxes, bins, or container for growth of larvae and treatment on biowaste
- Reactor for refinement of larvae

Type of incoming streams

- Organic waste: animal manure, human excreta, fruit, biowaste, vegetable waste, organic fraction of municipal solid wastes, millings and brewery side streams
- Insects: *Hermetia illucens* L. (Diptera: *Stratiomyidae*) larvae age typically 4–9 days (1–2 mg)

Operation

- Input organic materials moisture should be adjusted to 70-80%
- 100–125 mg feed/larva/day (based on 60% moisture content). All at once or periodic feeding
- Development time: 15–52 days
- Separation of Black Solider Fly (BSF) larvae (BSFL) from process residues
    - Sieving (70–299 mg, 6–20 mm)
    - Ramp where larvae can climb before prepupae stage to facilitate separation
- Refinement of larvae: killing, cleaning, sterilisation, drying and fractionation (proteins, lipids and chitin)
- Process influenced by: pH, container dimensions, temperature, larval density, humidity, feeding rate, feeding intervals.

Maintenance

- Maintenance of larvae refinement reactor

Connecting NBS units

- Not applied

Connecting supporting units

- Pre-treatment of the biowaste (e.g. particle size reduction, dewatering, removal of inorganics)

OUTPUTS

Type of outgoing streams

- Gaseous emissions (66% of C to CO_2), 50% of N to NH_3
- Larval biomass (32–58% proteins, 15-39% lipids based on DW / (12% of C, 10% of N and less than 3.5% of P))
- Compost like residue (similar to immature compost)

Co-benefits and limitations

- Pathogens numbers in the feed are reduced
- Pharmaceuticals and pesticides are not taken up by larvae
- Pharmaceutical and pesticides are reduced in biowaste after treatment with soldier fly

Risks

- Challenges: operation reliability and efficiency need to be improved, low TRL/economy of scale; missing benchmark for products, incomplete or restrictive regulations
- Lack of standard operating procedures: feeding rate and interval, biowaste description, genetics, larval density, temperature and time of harvest
- Potentially toxic metals are taken up by BSFL and may exceed animal feed regulations
- Fate of parasites and viruses unclear
- Smell

Connecting NBS units

- Composting (NBS 23)

- Solid waste anaerobic treatment (NBS 26)
- Aquaponics (NBS 47)

Connecting supporting units

- Mechanical processing (i.e. compost sieving)
- Post-treatment of the larvae (e.g. drying, protein and lipid extraction)

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STREET TREES / ROAD VEGETATION (NBS 39)

INPUTS

Construction

- Pits or concrete/modular/built box to limit the growth of roots towards infrastructure
- Soil + compost + Biochar (appropriate growth media)
- Drainage layer at the bottom
- Tree seedlings of proper age (non-allergenic)
- Irrigation system (not necessary but recommended)
- Sufficient area for surface infiltration in case of no irrigation
- Manpower for digging the pit, transporting the substrate and trees (city trees are planted at a height of > 5 m)

Type of incoming streams

- Manpower (for breeding, raising and planting)
- The trees themselves need to be transported to the city, usually from outside

- Compost/fertilizer/biochar at planting and for maintenance (depending on soil type and tree species)
- Irrigation water (reclaimed water / surface-groundwater)

Operation

- Irrigation
- Fertilization
- Street cleaning (fall-off leaves, flowers, fruit, seeds etc.)

Maintenance

- Tree care (e.g., pruning, cutting branches, shaping when needed)
- Cutting at the end of a lifetime

Connecting NBS units

- Composting (NBS 23)
- Solid digestate from AD systems
- Harvested algae from photobioreactors (NBS 48)
- Treated water from treatment wetlands (NBS 21)
- Retained water from wet and dry retention ponds (NBS 5, 6)

Connecting supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Membrane unit filtration (SU 8)
- Biochar (SU 6)
- Advanced oxidation (SU 10)
- Disinfection (SU 5)

OUTPUTS

Type of outgoing streams

- Wood biomass (aboveground wood biomass is not expected to accumulate pollutants*)
- Leaf biomass (may contain pollutants such as dust particles, heavy metals, PAHs)
- Evapotranspiration
- Fruit and seed biomass (may contain pollutants – effects on further use)

Co-benefits and limitations

Ecosystem services:

- Microclimate/temperature regulation (cooling, shade)
- Carbon sequestration
- Wind and noise mitigation
- Air purification (PAHs, micro-dust, heavy metals)
- Rainwater treatment and uptake (reduction of surface runoff)
- Reduction of water and wind erosion of soil
- Soil improvement and treatment
- Improved biodiversity (birds, insects)
- Creation of green corridors, e.g., as steppingstones for animal and plant species
- Glare reduction
- Support for pollinators

- Genetic resources
- Enhanced biodiversity in city caused by planting non-native street trees
- Social and cultural benefits
- Psychological, aesthetic or recreational benefits
- Groundwater recharge
- Educational services
- Economic benefits that result from above ecosystem services, e.g. property values

Risks

- Allergic potential of trees: tree pollen (e.g. from *Fraxinus*, *Platanus*, *Betula*, *Salix*…)
- Poisonous trees (rare, e.g., *Aesculus hippocastaneum*, Taxus sp.)
- Emissions of biogenic volatile organic compounds (BVOC), e.g., terpenes and isoprene that promote ozone formation
- Trees damage people or infrastructure: e.g., broken branches during storms, slippery sidewalks, pushing up street surface with roots

Connecting NBS units

- Composting (NBS 23)
- Anaerobic treatment (NBS 26)

Connecting supporting units

- Production of wood chips
- Biochar (SU 6)

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- See also references recommended for large urban parks and pocket gardens

LARGE URBAN PARKS AND POCKET GARDENS (NBS 40, 41)

INPUTS

Construction

- Landscaping
- Construction of walking paths, cycling lanes, banks, recreational facilities (open air fitness, playground facilities for kids, educational/informational equipment – boards, pavilions, green living rooms, open stages)
- Fences when needed
- Dog park (fenced)
- Additional soil + compost (appropriate growth media)
- Tree, shrub, flowers, herbs seedlings of proper age (non-allergenic)
- Irrigation system (not necessary but recommended)
- Optional ornamental artificial pond: excavation, impermeable layers, planting boxes for aquatic plants, seedling, water source, fish, turtles, frogs
- Optional greenhouses (tropical, overwintering, butterfly)
- Revitalized small streams located the park (landscaping, see NBS units for river restoration)
- NBS units for rainwater management can be integrated in the park
- Houses for insects and beehives, birdhouses
- Waste bins as part of city infrastructure
- Toilets as part of city infrastructure or remote facilities

Type of incoming streams

- Compost/fertilizer at planting and for maintenance (depending on soil type and tree species)
- Irrigation water (reclaimed water, greywater, rainwater)
- Lawn fertilizers

Operation

- Footpath's cleaning (fall off leaves, flowers, seeds etc.)
- Protection measures for sensitive species/ecosystems and protected species
- Bee keeping
- Insect keeping
- Harvesting
- Biomass/organic material processing (e.g. composting)
- Irrigation/fertigation

Maintenance

- Fertilization
- Horticulture activities: cutting branches, shaping when needed, mowing of grass and ornamental plants
- Maintenance of park infrastructure (recreational and educational facilities, banks, pathways…)
- Monitoring of water quality and biodiversity
- Urban forest management (in case forests are a part of park, see NBS urban forest)

Connecting NBS units

- Composting (NBS 23)

- Solid digestate from anaerobic treatment (NBS 26)
- Harvested algae from photobioreactors (NBS 48)
- Treated water from treatment wetlands (NBS 21)
- Retained water from wet and dry retention ponds (NBS 5, NBS 6)

Connecting supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Membrane filtration (SU 8)
- Biochar (SU 6)
- Advanced oxidation (SU 10)
- Disinfection (SU 5)

OUTPUTS

Type of outgoing streams

- Wood and plant biomass
- Mowed grass
- Leaf biomass
- Trees' fall-off (non-edible fruits, seeds)
- Dog feces in plastic bags
- Compost from in case of composting on site

Specific to large urban parks:

- Fish biomass
- Garbage waste

Specific to pocket gardens:

- Fruits (edible)

Co-benefits and limitations

- Microclimate regulation
- Wind and noise mitigation
- Reduction of water and wind erosion of soil
- Aesthetics
- Air purification (PAHs, micro-dust, heavy metals)
- Increase of biodiversity (birds, insects, bees, wildlife)
- Pollination
- Soil improvement and treatment
- Glare reduction
- Economic benefits that result from above ecosystem services
- Social benefits (recreation, gardening, relaxation, socialisation, education, fishing, culture…)
- Compost production

Specific to large urban parks:

- Rainwater management
- Food source (fruit trees, berries, mushrooms, herbs, edible plants, fish)

Specific to pocket gardens:

- Mitigate stormwater runoff events (parks)
- Green corridor effect
- Food source (fruit trees)

Risks

- Allergic potential of trees: tree pollen (e.g. from *Fraxinus* sp., *Platanus* sp., *Betula* sp., *Salix* sp. Etc.)
- Poisonous trees (rare, e.g., *Aesculus hippocastaneum*, *Taxus* sp.)
- Emissions of biogenic volatile organic compounds (BVOC), e.g., terpenes and isoprene that promote ozone formation
- Trees damage people or infrastructure: e.g., broken branches during storms, slippery sidewalks, pushing up street surface with roots

Connecting NBS units

- Composting (NBS 23)
- Anaerobic treatment (NBS 26)

Connecting supporting units

- Production of wood chips
- Biochar (SU 6)

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- See also references recommended for street trees and road vegetation

PHOTOBIOREACTORS (open raceway ponds or closed (NBS panel systems) 48)

INPUTS

Construction

Open raceway ponds:

- Light source (sunlight + artificial source)
- Shallow pond (excavation)
- Mixing unit (e.g. paddle wheel or pump)
- CO_2 blowers
- Greenhouse (optional)

Closed panel system:

- Light source (mostly artificial source)
- Photobioreactor glass tubes, bags or similar for vertical or horizontal setting
- Mixing unit (pump, see waves when installed on sea surface as floating system)
- CO_2 injector

- Greenhouse (optional)
- Storage tank for fertilizers and system for application in case of algae cultivation on tap water or rainwater

Type of incoming streams

- Inoculum of algal communities
- Nutrients (e.g. primary or secondary treated wastewater, black water, source separated urine, digestate from biogas plant, wastewater from food production industry)
- Carbon dioxide (e.g. with aeration, from industrial sources or combusted CH4 gas)
- Light (natural or artificial)

Operation

- Mixing or waving
- CO_2 injection
- Temperature and pH control
- Supply of inoculum culture
- Algae biomass harvesting (flocculation, settler)-supporting unit

Maintenance

- Monitoring for treated water quality
- Removal of settled biomass
- Monitoring of algae culture or algae-bacteria culture
- Monitoring of pH, CO_2 ratio

Connecting NBS units

- Anaerobic treatment (NBS 26) for liquid digestate supply
- Aerobic water treatment (NBS 27)

Connecting supporting units

- Reservoir for inoculum cultivation and storage

OUTPUTS

Type of outgoing streams

- Treated water (treated blackwater or urine, treated municipal WW, treated digestate from biogas plant)
- Algal biomass, (e.g. for direct use as organic fertiliser, indirect as biofuel, biostimulants, cosmetic/pharmaceutical industries; biostimulants for agriculture, animal feed)

Co-benefits and limitations

- Removal of nutrients (N, P) from wastewater
- Potential to have high-value compounds in the biomass (e.g. biostimulants, pigments)
- Potential removal of CO_2 from e.g. industrial gas streams (only in well-designed systems)
- Polishing of treated wastewater e.g. MPs, pathogens, micro-pollutants (under research)

Risks

- Culture contamination by fungi, zooplankton, viruses
- Inappropriate pH, CO_2 control
- Inefficient CO_2 injection (bubble size, pressure)
- inefficient algal biomass harvesting
- Seasonal algae die-off, winter operation (operation costs increase)

- Self-shading, weak biomass control
- Open system sensitive weather conditions
- Glass/plastic waste in case of closed system

Connecting NBS units

- Anaerobic digestion (NBS 26)

Connecting supporting units

- Solid/liquid separation systems (settler, membrane, flotation, flocculation, centrifugation, micro-screening) (SU 7)
- Advanced oxidation (SU 10) treatment for reclaimed water production
- OP/UV disinfection (SU 5) for reclaimed water production
- Membrane filtration (SU 8) for reclaimed water production

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ANAEROBIC TREATMENT FOR CH_4 AND VFA (ADD) PRODUCTION

Systems with biomass retention	Systems without biomass retention
INPUTS	
Construction	
• for example, PE100 for the reactor plus metal subunits • pipes and pumps • use of CH_4 gas • stainless steel tanks	• for example, PE100 for the reactor plus metal subunits • Pipes and pumps • Use of CH_4 gas
Type of incoming streams	
• Blackwater / kitchen refuse • Industrial organic residues • COD concentration between 10–50 g COD/L If the ambient temperature is	• Blackwater / kitchen refuse • Industrial organic residues • COD concentration ca > 50 g COD/L

≥ 20 °C, then also concentrations below 10 g COD/L can be allowed • no further input streams needed, provided enough nutrients are present • Depending on the flow of the waste stream different systems can be used	• Normally, no further input streams needed (provided enough nutrients are present, which normally is the case for domestic waste streams
Operation	
• Mesophilic conditions (≥ 20 °C - 35° C); thermophilic (55°C) conditions are researched for more concentrated streams • (semi) continuous flow	• Mesophilic conditions (≥ 20 °C-35 °C) • (semi) continuous flow • Mixing
Maintenance	
• Removal of potential scums layers • Regular sludge discharge, e.g. once a month	• Removal of potential scums layers • Maintenance of the settling layer in CSTR system
Connecting NBS units	
• Not applied	• Not applied
Connecting supporting units	
• Source separation Toilet (ADD) • Vacuum unit (ADD) • Kitchen grinder for kitchen refuse*	• Source separation Toilet (ADD) • Vacuum unit (ADD) • Kitchen grinder for kitchen refuse
OUTPUTS	
Type of outgoing streams	
Liquid effluent • ca 30–40% of the input COD concentration • ca 60–70% of the input P concentration • ca 70–80 % of the input N concentration • ca 90% of the input K concentration • Micro-pollutants • Micro-nutrients • Pathogens Sludge • ca 10–20% of the input COD concentration • ca 30–40% of the input P concentration	Effluent: • ca 50% of the input COD concentration • 100% of the input P concentration • 100 % of the input N concentration • 100% of the input K concentration • Micro-nutrients • Micro-pollutants • Pathogens Biogas • Ca 50% of input COD converted to CH_4. Biogas also contains (depending on nature input) 20–40% CO_2 and other (trace) gasses.

• ca 20–30 % of the input N concentration • ca 10% of the input K concentration • Micro-pollutants • Micro-nutrients • Pathogens Biogas • Ca 40-60% of input COD converted to CH_4. Biogas also contains (depending on nature input) 20-40% CO_2 and other (trace) gasses.	
Co-benefits and limitations	
• Energy production instead of consumption when applying aerobic treatment. • Nutrients are retained in the effluent and can be recovered for use as a fertiliser in agriculture • Sludge can be reused in agriculture after a disinfection step	• Energy production instead of consumption when applying aerobic treatment • Nutrients are retained in the effluent and can be recovered for use as a fertiliser in agriculture
Risks	
• Poor pathogen removal (except for the thermophilic systems) • Explosive risks	• Poor pathogen removal • Effluent contains non converted CODs (including biomass) • Explosive risks
Connecting NBS units	
• Photobioreactors (NBS 48) • Treatment wetlands (NBS 21) • Aerobic water treatment (NBS 27)	• Photobioreactors (NBS 48) • Treatment wetlands (NBS 21) • Aerobic water treatment (NBS 27)
Connecting supporting units	
• A flare or gas storage is needed to prevent emission of excess methane gas* • Sulfur treatment unit for biogas use for power and/or heat production* • Nutrient recovery unit (P and N precipitation and stripping) • Membrane systems (disinfection, removal of remaining COD and organic micropollutants)	• A flare or gas storage is needed to prevent emission of excess methane gas* • Sulfur treatment unit for biogas use for power and/or heat production* • Solid/liquid separation system (membrane, settler, …) • Nutrient recovery unit (P and N precipitation and stripping) • Membrane systems (disinfection, removal of remaining COD and organic micropollutants)

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AEROBIC (POST) TREATMENT (including Nitrification of Urine) (NBS 27)

INPUTS

Construction

- For example, PE100 for the reactor plus metal subunits
- Aeration unit

Type of incoming streams

- Grey water with a COD of ca 0.5 g/L or pre-treated grey water (e.g. bioflocculation) with a COD of ca. 250 g COD/L
- Oxygen (air)
- Anaerobically treated black water after nutrient recovery
- Urine

Operation

- Continuous flow or SBR
- Supply of oxygen
- No temperature control
- Different redox zones for N & P removal
- Potentially including a membrane (MBR)

Maintenance

- Pump and piping systems
- Compressed air systems and blowers

Connecting NBS units

- Anaerobic digestion unit (NBS 26)

Connecting supporting units

- Source separation toilet (urine) (ADD)
- Evaporation system
- Odour control units (e.g. biofilter)

- Nutrient recovery unit (P and N precipitation and stripping) (SU 3, SU 4)

OUTPUTS

Type of outgoing streams

- Liquid effluent, quality (N&P content) depending on set-up for N&P removal; high COD removal (up to 90%)
- Sludge (Ca 40% of incoming COD)

Co-benefits and limitations

- High effluent quality
- If combined with MBR reuse of high-quality water is possible and allows for compact, small footprint and low sludge production

Risks

- Effluent may still contain significant nitrogen and phosphorus concentrations (eutrophication risk)

Connecting NBS units

- Treatment wetlands (NBS 21)

Connecting supporting units

- Solid/liquid separation unit (e.g. settler) (SU 7)
- Adsorption; activated carbon unit for micropollutants removal (SU 9)
- Disinfection (UV, free chlorine) (SU 5)

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DECENTRALIZED SOLID WASTE ANAEROBIC (ADD) TREATMENT IN URBAN AREAS

INPUTS

Construction

- Processes with treatment capacity from 10 to 200 t/year for micro-anaerobic digesters (micro AD)
- These technologies can be classified into two main groups:
  - Continuous technologies
  - Batch type technologies

Type of incoming streams

- Organic fraction of the municipal solid waste
- Food waste (FW)
- Co-substrate (Green waste from private gardens, Green waste from public areas, Paper towel from mass and commercial catering)
- Liquid addition for adjusting humidity level

Operation

- Sludge retention time (SRT): 30-40 days
- Temperature mostly mesophilic AD (35 to 40°C)
- In the case of batch mode process: multiple batches needed for flattening the biogas production rate in time
- In the case of semi-continuous process (daily or weekly)
- pH monitoring
- Liquid percolation and recirculation

Maintenance

- Pump and piping for continuous systems
- Sand settling layer removal for continous systems
- Scum layer prevention
- Sulfur filter exchange
- For batch systems filling/emptying required and leave sufficient inoculum for the next batch

Connecting NBS units

- Not applied

Connecting supporting units

- Pre-treatment units (including a sorting step, a storage step, a shredding step, a water addition step and/or a mixing step)

OUTPUTS

Type of outgoing streams

- Liquid and solid digestates (fertilizers, organic amendments)
- Biogas

Co-benefits and limitations

- Keep fertilizers and organic amendments in urban areas

Risks

- Odour generation during storage of biowaste
- The design of the micro AD equipment should take into account size limitations of the local urban planning rules
- Biogas leakages
- Explosive risks
- Pathogen risks

Connecting NBS units

- Composting (NBS 23)
- Hydroponics (NBS 45)
- Photobioreactors (NBS 48)

Connecting supporting units

- Sulphur treatment unit for biogas use for power and/or heat production
- Solid/liquid separation unit (SU 7)
- Nutrient recovery unit (P and N precipitation and stripping) (SU 3, SU 4)
- Evapo-concentration to recover fertilizing nutrients
- Gas treatment and injection units for direct injection in national gas network

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Table S2 Supplementary Materials B

NBS supporting units

The NBS supporting units described in this paper and their attributed numbers (given in brackets) are extracted from the complete list of NBS supporting units given in the introductory paper that presents a framework for addressing circularity challenges in cities with NBS (Langergraber et al., 2021). However, new NBS supporting units are being described and applied to enable more efficient resource recovery in the cities; therefore, also additional NBS supporting units are addressed in this paper and described below – market as additional (ADD).

SOLID/LIQUID SEPARATION, CENTRIFUGATION, SETTLING TANK (SU 7)

INPUTS

Construction

Ultrasound sedimentation unit for separation of algae-bacterial biomass from photobioreactors (in development):

- excavation (optional; can be aboveground)
- concrete or prefabricated plastic impermeable basin with 1 chamber
- inflow and outflow pipes and pumps
- ultrasound unit

Sludge dewatering units:

- Centrifugation
    - centrifugation unit
    - pump
    - polymer dosage
- Belt (filter) press as a dewatering system:
    - pump
    - polymer dosage
    - press
- Sludge cake conveyor
    - compressed air pump
- Sludge drying bed:
    - area, or bed
    - drainage system
    - plants (e.g. *Phragmites australis*)

Settling tank:

- Circular or rectangular tanks
- Pumps
- Collection tank (incoming stream greywater)

Type of incoming streams

- Ultrasound sedimentation unit: algae-bacteria biomass from photobioreactors, blackwater, greywater
- Centrifugation: primary & secondary aerobic sludge (1-8% TS), anaerobically digested biosolids (1-20%)
- Belt (filter) press: primary & secondary aerobic sludge (1-8% TS), anaerobically digested biosolids (1-20%)

- Sludge drying bed: digested solids (sludges), 60-160 kg TS m^{-2} year
- Settling tank: wastewater (grey), blackwater, faeces, brownwater, organic solid waste

Operation

- Ultrasound sedimentation unit: wavelength, duration of operation
- Centrifugation: polymer addition (to reach desired dewatering level) (2.5-15 g/kg TS)
- Belt (filter) press: polymer addition (to reach desired dewatering level) (1.5-12.5 g/kg TS)
- Sludge drying bed: loading rates
- Settling tank: hydraulic retention time

Maintenance

- Ultrasound sedimentation unit
    - regular removal of accumulated algae-bacterial biomass
    - service and replacement of ultrasound unit and pumps (every ca 5 years)
- Centrifugation: odour control/ventilation
- Belt (filter) press: service and replacement of press and pumps.
- Sludge drying beds: removal of accumulated biomass (every ca 5-10 years)
- Settling tank: scum removal and desludging

Connecting NBS units

- Photobioreactor (48)
- Anaerobic treatment (26)
- Aerobic treatment (27)
- Treatment wetland (21)

Connecting NBS supporting units

- Adsorption, activated carbon (S9)
- Biochar/Hydrochar (S6)

OUTPUTS

Type of outgoing streams

Ultrasound sedimentation unit:

- algae-bacterial biomass to be used directly or indirectly as a fertilizer, biostimulants, biofuel, feed etc. and treated effluent from photobioreactor for irrigation/fertigation
- blackwater: nutrient rich stream (comparable to UASB) plus primary sludge as a resource recovery
- greywater: low solid effluent (irrigation) plus primary sludge as a resource recovery

Centrifugation

- Dry sludge cake (20-30%) plus
- Centrate (liquid phase) needs to be used for resource recovery

Belt press: very dry sludge cake plus nutrient rich liquid to be used…

Sludge drying beds: dry matter (compost) as a fertilizer, soil improvement

Settling tank: liquid to be used for resource recovery (irrigation water), biosolids for resource recovery

Co-benefits and limitations

- Dry material (less transport costs, if any)
- Centrifugation: grit removal necessary, skilled personnel

- Belt press: hydraulically limited in high throughput, sludge grinder required; sensitive to incoming sludge feed characteristics; no automatic operation
- Sludge drying beds: large area, stabilised sludge for soil improvement, labour intensive, low operation costs
- Settling tank: simple technique, regular removal of scum and biosolids needed

Risks

- Ultrasound sedimentation unit: unstable efficiency, resuspension
- Centrifugation: potential high SS in centrate
- Sludge drying beds: climatic effects
- Odour
- Sludge loaded with potentially toxic pollutants (e.g. metals)

Connecting NBS units

- (public) Green spaces (NBS 37–43)
- Productive gardens, urban forest, urban farms and orchards (NBS 49-51)
- Soil improvement and conservation (NBS 33)
- Vertical greening systems & green roofs (NBS 13–20)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Disinfection (SU 5)
- Membrane filtration (SU 8)

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Urine Diverting TOILETS (ADD)

INPUTS

Construction

- Ceramic, plastics, metal

Type of incoming streams

- Human excreta
- Toilet paper or other cleansing material
- Bulk material (composting toilet)
- Air (for ventilation of dry toilet)
- Water (flush toilet)
- Electricity (for ventilation of dry toilet)

Operation

- Addition of bulk material (in separating composting toilet)
- Flushing of faeces (in non-dry separating toilets)

Maintenance

- Cleaning
- Maintenance of mechanical parts or ventilation (composting toilet)
- Prevention of clogging (precipitation)/addition of acid
- Emptying of compost chamber (composting toilet)

Connecting NBS units *(indirectly to food and biomass production)*

- Aquaculture (NBS 44)
- Hydroponic and soilless technologies (NBS 45)
- Organoponic/Bioponic (NBS 46)
- Aquaponic farming (NBS 47)
- Productive garden (NBS 49)
- Urban farms and orchards (NBS 51)

Connecting NBS supporting units

- -

OUTPUTS

Type of outgoing streams

- Faecal free Urine + water (depending on flushing system)
- Faecal matter, cleansing material, bulk material (composting toilet)
- Faecal matter, cleansing material with water (flush toilet)

Co-benefits and limitations

- Nutrient recovery possible
- Soil conditioner from composted human faecal matter possible
- Substantial water saving
- Storage, handling, and processing of urine: e.g., possible ammonia loss

Risks

- Micro-contaminants in faecal matter and urine
- Risk related to composting. Pathogens, too much or too little water

Connecting NBS units

- Anaerobic treatment (NBS 26)
- Aerobic (post) Treatment (NBS 27)
- Composting (NBS 23)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Disinfection (SU 5)

FURTHER READINGS

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- Ecodomeo: https://www.ecodomeo.com/
- Ecosec: http://ecosec.fr/references/
- Wostman: https://www.wostman.se/en/products

WATER FREE URINAL	**(ADD)**
INPUTS	
Construction	
• Lightweight high-tech polycarbonate or ceramic urinal • MB Active Trap • Transport pipe urine to storage	
Type of incoming streams	
• Urine	
Operation	
• MB Active Trap should be replaced after 7000 urinations	
Maintenance	
• Cleaning • Use of acid for avoiding precipitation	
Connecting NBS units ***(indirectly to food and biomass production)***	
• Aquaculture (NBS 44) • Hydroponic and soilless technologies (NBS 45) • Organoponic/Bioponic (NBS 46) • Aquaponic farming (NBS 47) • Productive garden (NBS 49) • Urban farms and orchards (NBS 51)	
Connecting NBS supporting units	
• -	
OUTPUTS	
Type of outgoing streams	
• Urine	
Co-benefits and limitations	
• No water use; therefore, large water saving	

- No connection to drinking water tap

Risks

- Microcontaminants (hormones, pharmaceuticals) in collected urine

Connecting NBS units

- Aerobic (post) treatment (NBS 27)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)

FURTHER READINGS

- https://www.saniwijzer.nl/projecten/afas-live/detail=13 (in Dutch)
- https://www.saniwijzer.nl/projecten/villa-flora/detail=76 (in Dutch)

Water saving/water-free toilets without urine diversion) (ADD)

INPUTS

Construction

- Ceramic, plastics, metal toilets
- Vacuum collection system, including a vacuum pump or composting chamber
- Small diameter piping (vacuum)
- Foam Flush toilet and adapted tubing

Type of incoming streams

- Human excreta
- Toilet paper or other cleansing material
- Bulk material (composting toilet)
- Air for ventilation (composting toilet)
- Water (flush toilet)
- Electricity (vacuum toilet)
- Water
- Biodegradable soap (foam flush toilet)

Operation

- Electricity (for vacuum, ventilation, foam flush)
- Refilling of biodegradable soap (foam flush)
- Creating a vacuum by pump (vacuum toilet)

Maintenance

- Use of organic acid to prevent precipitates in tubing and pump
- Cleaning

Connecting NBS units *(indirectly to food and biomass production)*

- Aquaculture (NBS 44)
- Hydroponic and soilless technologies (NBS 45)
- Organoponic/Bioponic (NBS 46)
- Aquaponic farming (NBS 47)
- Productive garden (NBS 49)
- Urban farms and orchards (NBS 51)

Connecting NBS supporting units

- -

OUTPUTS

Type of outgoing streams

- Blackwater, including maximum 1 litre flush water per flush
- Ash (incinerating toilet)

Co-benefits and limitations

- Substantial water saving
- Concentrated output (black water) allows energy production (anaerobic treatment) and nutrient recovery (for example struvite precipitation)
- Use of small diameter piping
- Toilet installation is flexible (anywhere in the house/office)
- Ultra-vacuum toilets with even lower flush volume (0.5 l $flush^{-1}$)

Risks

- Relies on electricity (VC, CT, foam flush)
- (risk related to composting. Pathogens, too much or too little water)

Connecting NBS units

- Anaerobic treatment (NBS 26)
- Aerobic treatment (NBS 27)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Disinfection (SU 5)
- Biochar/hydrochar (SU 6)
- Solid/liquid separation (SU 7)

FURTHER READINGS

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- https://www.saniwijzer.nl/projecten/desah---lemmerweg-oost-ii/detail=483 (in Dutch)
- https://www.saniwijzer.nl/projecten/desah---noorderhoek-zwartwaterbehandeling/detail=52 (in Dutch)
- https://www.saniwijzer.nl/projecten/villa-flora/detail=76 (in Dutch)
- https://www.saniwijzer.nl/projecten/nioo-knaw/detail=66 (in Dutch)
- Project Run4life - Demonstration sites https://run4life-project.eu/demosites/
- https://www.hamburgwatercycle.de/en/the-jenfelder-au-neighbourhood/the-hwc-in-the-jenfelder-au
- https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/59
- https://bullittcenter.org/building/building-features/waste-not/
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DISINFECTION (UV, CAVITATION, OZONE, CHLORINATION) (SU 5)

INPUTS

Construction

- UV lamps
- Reactors (concrete)
- Pumps
- Storage tank for chemicals

Type of incoming streams

- Treated effluent of biological systems
- Concentrated streams (thermal disinfection)
- Solid free water

Operation

- Chemicals (chlorine from liquid solution or generated onsite via electrolysis)
- Energy/electricity
- Check turbidity

Maintenance

- Cleaning (biofilm and scaling on UV lamps)
- Monitoring the intensity of UV light (energy, wavelength)
- Check occurrence of undesired crystallisation

Connecting NBS units

- Anaerobic treatment (NBS 26)
- Aerobic (post) treatment (NBS 27)
- Composting (NBS 23)

Connecting NBS supporting units

- Rainwater harvesting (SU 1)
- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)
- Adsorption (SU 9)

OUTPUTS

Type of outgoing streams

- Pathogen free water
- Pathogen free solid streams (after disinfection)

Co-benefits and limitations

- Potential removal organic MP (depending on the type of MP)
- Ozone only for meso/macro scale

Risks

- -

Connecting NBS units

- Composting (NBS 23)
- Aquaculture (NBS 44)
- Hydroponic and soilless technologies (NBS 45)
- Aquaponic farming (NBS 47)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)
- Adsorption (SU 9)

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PHOSPHORUS PRECIPITATION AND RECOVERY (SU 3)

INPUTS

Construction

Treatment wetlands:

- Mixing the media (sand) with calcite, crushed marble or other materials to increase P-binding capacity. Additional (external) filtering unit can also be constructed where the media can be easily replaced after being saturated with P.
- P precipitation with aluminium salts in sedimentation tank prior to the wetland (aluminium polychloride (PAC) dosed by an airlift pump)

Treatment of source-separated black water:

- Precipitation with Mg or Ca in separate tank, typically after anaerobic treatment of black water in a CSTR or UASB reactor for biogas recovery.
- Typically, Mg-struvite is formed by crystallization after addition of a Mg-salt such as $MgCl_2$ and/or in combination with pH increase > 9.0
- The produced struvite (mostly $MgNH_4PO_4 \cdot 6H_2O$) allows to recover P, which is listed as a critical raw material in the European Union, and mainly serves as fertilizer.

Treatment of source-separated urine:

- 94% struvite precipitation efficiency but merely 55% of the crystals were removed and recovered. pH controlled at pH=4 to remove CO_2. Then treatment in 2 m^3 4 HRT reactor. NaOH, 50%) addition to ensure a pH of greater than 8.5. The removal of CO_2 in the previous stage reduces the buffering capacity of the urine, and thus little NaOH was needed to raise the pH to 8.5. Based on the measured phosphate concentrations in the CO_2

stripping tank, magnesium salt was dosed into the struvite reactor at a ratio of 1.6 mol Mg mol^{-1} P. The form of magnesium salt used was $MgCl_2$ $6H_2O$ initially, then MgOH, settling tank (2 m^3, 4-h) HRT)

Phosphorous recovery using different reactive filter media

- Reactive filter media (like Polonite®, Filtralite®) with excellent capabilities of capturing phosphorus from both wastewater, and runoff water from farmland are used for phosphorus removal and recovery. They enable recycling the vital nutrient by returning it on productive farmlands.
- Polonite is a natural calcium silicate, achieves a phosphorus reduction of 100% in sewage water for new installations and over 90% if employed for a longer period of time. The technology function of Polonite is proven by over 20 years of research at The Royal Institute of Technology in Stockholm (KTH) and through over 6000 installed filter solutions for sewage.
- Filtralite® Nature P 0.5-4 filter media, produced from expanded clay material, with its highly porous structure, enables large microbial growth surface for biological filtration which means improved filter capacity and reduced operational costs. Filtralite® Nature P media, with its high content of limestone, improves phosphorus removal from waste and effluent waters.

Type of incoming streams

Treatment wetlands:

- In case of P precipitation with PAC approx. 30 L of PAC per year per household is needed to reach <1.5 mg/L of total phosphorous at the outflow. Treatment of source-separated black water/urine:
- Blackwater UASB effluent or Black water CSTR effluent after solid separation
- Urine from water free urinal or separation toilet

Phosphorous recovery using different reactive filter media

- Urban storm water
- Domestic/household wastewater

Operation

Treatment wetlands:

- TW with P-sorbing media: P monitoring to check the filter saturation

Treatment of source-separated blackwater/urine:

- many operational conditions influence the crystallization process and struvite quality: influent P concentration, crystal retention time, TSS concentration, viscosity, presence of colloidal substance, Mg:P ratio, temperature, pH and mixing conditions;
- addition of Mg: $MgCl_2$, $Mg(OH)_2$, MgO, to ratio's of Mg:PO_4 of 1:1 and higher. 90% removal of P observed in black water at ratio 1.5:1 at pH=8 and 1.3:1 at pH=9 in vacuum collected blackwater;
- pH increase: base addition, CO_2 stripping, and other methods;
- the need for chemical addition might make the small-scale treatment of (anaerobic) effluents less feasible.

Phosphorous recovery using different reactive filter media

- Efficiency of phosphorus recovery process depends of type used reactive filters materials
- There are many operational conditions influencing the filtration process: hydraulic retention time, pH control, influent P concentration

Maintenance

Treatment wetlands:

- TW with P-sorbing media: P monitoring to check the filter saturation
- Adding new PAC solution

Treatment of source-separated black water/urine:

- pH control
- Addition of chemicals and maintenance of dosing pumps
- Maintenance of mixer, piping and pumps (regular check for unwanted precipitation)
- Harvest of the struvite crystals

Phosphorous recovery using different reactive filter media

- pH control
- monitoring P level in effluent

Connecting NBS units

- Anaerobic treatment (NBS 26)
- Aerobic treatment (NBS 27)

Connecting NBS supporting units

- Ammonia stripping (SU 4)
- Disinfection (SU 5)
- Solid/liquid separation (SU 7)
- Separating toilets (SU 11)
- Water free urinal (SU 12)

OUTPUTS

Type of outgoing streams

Treatment wetlands (TW):

- TW with P binding material: inorganic media (calcite, marble) with adsorbed P
- Primary sludge enriched with P-PAC

Treatment of source-separated blackwater/urine:

- A large-scale and comprehensive study of the composition of struvite crystals has been carried out on 24 European production plants, accounting for 30% of the 80 struvite installations worldwide. Differences in morphology and particle size distribution were observed for struvite produced from different sources, but all samples showed a heavy metal content below the legal limits. In conclusion, the results highlight the suitability of most struvite to enter the EU fertilizer market.

Phosphorous recovery using different reactive filter media.

- There are thousands of installations with reactive filter media. Long-term phosphate removal in wastewater filtration systems is achieved.

Co-benefits and limitations

Treatment of source-separated blackwater/urine:

- Removal of P -and partially N- in the blackwater treatment line as struvite, reduces the use and need of chemicals ($FeCl_3$ for phosphate and COD source for denitrification) and energy (aeration for nitrification) for further downstream treatment of the wastewater.
- Controlled precipitation and recovery of struvite avoids the formation of unwanted precipitation further downstream which can cause severe clogging or damaging to pumps and piping.
- The examples above mainly focussed on ammonium-struvite, but K-struvite ($MgKPO_4 \cdot 6H_2O$) or MKP is also an interesting fertilizer. K-struvite crystallization is an attractive technology to simultaneously recover phosphate and potassium from urine as well. Another example to recover P from wastewater is precipitation of calcium phosphate, e.g. as hydroxyapatite (HAP)

Risks

- Presence of organic material
- Potential bad smell of struvite (depends on source material)

Connecting NBS units

- (public) Green spaces (NBS 37–43)
- Productive gardens, urban forest, urban farms and orchards (NBS 49-51)
- Soil improvement and conservation (NBS 33)
- Vertical greening systems & green roofs (NBS 13–20)

Connecting NBS supporting units

- Ammonia stripping (SU 4)
- Disinfection (SU 5)
- Adsorption (SU 9)

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AMMONIA STRIPPING (SU 4)

INPUTS

Construction

- Strip tank
- Scrub tank
- Pre-treatment
- Packaging material
- Chemical dosage system

Type of incoming streams

- High N concentration: anaerobic digestate (only integrated stripper, not for digestate)/liquid effluent
- Urine

Operation

- TSS removal
- pH adjustment, pH= 8-12
- Gas flow: 600:1 to 1200:1
- Temperature 2- 60/80°C (for pH=7.5-8.5)
- One operation mode: two columns (2 strippers, 1 scrubber, 0.75 m^3, 0.3 m^3 packaging material ~ 178 m^2 m^{-3} surface area. T= 35-40°C, pH=9 controlled by 50% NaOH dosage. Stripper 1 (flowrate of 7 $m^3 h^{-1}$ with counter-flow of air from the bottom. stripper 2 (8 m^3 h^{-1} of effluent from stripper 1) HRT was 6.3 min for stripper 1, 5.5 min for stripper 2. Air in a closed-loop cycle (1500 $m^3 h^{-1}$). The produced ammonia-rich air is then fed through the bottom of the scrubber while sulfuric acid solution (H_2SO_4, 96%) is fed from the top at 6.5 $m^3 h^{-1}$. Counter-flows, 40% $(NH_4)_2SO_4$, was produced.
- Another operation mode: typical temperature of 25-35°C, pH 11 (nearly 100% shift from ammonium to ammonia)

Maintenance

- Refer to Metcalf and Eddy
- Check on clogging

Connecting NBS units

- Anaerobic treatment (NBS 26)
- Aerobic (post) treatment (NBS 27)

Connecting NBS supporting units

- Struvite precipitation (SU 3)
- Disinfection (SU 5)
- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)
- Separating toilets (SU 11)
- Water free urinal (SU 12)

OUTPUTS

Type of outgoing streams

- 5-83% of Nin removed
- The removal and recovery efficiencies for nitrogen were 93% and 85%

- 20-40% $(NH_4)_2SO_4$ solution

Co-benefits and limitations

- Actually produce solely N containing fertiliser (for example NH_4NO_3)
- Effluent ready for struvite precipitation
- Alternative process: vacuum thermal stripping in combination with sorption
- Bad smell of products
- High energy costs and chemicals
- Applicability of N-stripping application depends on local circumstances like scale, temperature, availability of sustainable energy

Risks

- -

Connecting NBS units

- (public) Green spaces (NBS 37–43)
- Productive gardens, urban forest, urban farms and orchards (NBS 49-51)
- Soil improvement and conservation (NBS 33)
- Vertical greening systems & green roofs (NBS 13–20)

Connecting NBS supporting units

- Phosphate precipitation (SU 3)
- Disinfection (SU 5)
- Adsorption (SU 9)

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BIOCHAR/HYDROCHAR PRODUCTION (SU 6)

INPUTS

Construction

- Muffle or stove for pyrolysis, torrefaction, gasification, or hydrothermal carbonization
- Organic carbon-rich material/C-rich biomass (dry [for biochar production] or wet [for hydrochar production]). Biochar can be produced from different types of biomass residues, including crop plants (e.g., rice husk, wheat bran), and as an intermediate product in bioethanol production (biowastes from the food processing industry). Hydrochar can be produced by wet animal manures, sewage sludge, and algae
- Physical conditions: in dry oxygen starved ambience at 200-900°C for biochar production, in subcritical water (at lower temperatures, 150-350°C) for hydrochar production

Type of incoming streams

- Appropriate chemical characteristics of biomasses (e.g. C-rich materials)
- Appropriate physical characteristics of biomasses (dry or wet, it depends if you want to produce biochar or hydrochar, respectively)

Operation

- Biomass collection
- Products and by-products recovery

Maintenance

- Checking plant system seal (e.g. troubles for high pressures/temperatures)

Connecting NBS units

- Solid waste anaerobic treatment (26)
- Treatment wetlands (21)
- Street trees/urban parks (39–41)
- Productive garden (49), urban forest (50), urban farms and orchards (51)
- Public green space (37-43)

Connecting NBS supporting units

- Solid/liquid separation unit (S7)
- Mechanical pre-treatment (shredding and mixing) (ADD)

OUTPUTS

Type of outgoing streams

- Biochar, hydrochar (material recovery and reuse)
- Ash
- Combustible gases (carbon monoxide [CO], methane [CH_4], and hydrogen gas [H_2]) for energy production
- Water
- Condensable tar (by-products; small amounts)
- Carbon sequestration
- Nutrient recovery (because of the production of N-rich products)

Co-benefits and limitations

- If used as soil physical and chemical improvers, biochar and hydrochar could improve nutrient management, increase soil carbon storage, enhance water infiltration and retention, encourage beneficial soil organisms and prevent soil compaction; it can also be used as peat substitute in peat-free substates in plant nurseries

Risks

- Heavy metals sources
- Landfill use (for tar)
- If used in high quantity as soil improvers, biochar and hydrochar could increase albedo

Connecting NBS units

- Public green space (NBS 39–41)
- Productive gardens, urban farms and orchards (NBS 49 and 51)
- Soil improvement and conservation (NBS 33)
- Green roofs and walls (NBS 13–20)

Connecting NBS supporting units

- Air treatment
- Leachate treatment
- Heat exchanger

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MEMBRANES (SU 8)

INPUTS

Construction

- Membranes
- Tank (optional, membranes can be placed outside)
- Pumps to pump water through membrane and create driving force for filtration
- Blower (in case when membranes cleaning can be done through backwashing)
- Pre-treatment (degree of treatment needed depends on the quality of incoming water)

Type of incoming streams

- Polluted waters, e.g. treated or untreated wastewater, rainwater, grey water, black water

- Avoid inert material (grid) otherwise pre-treatment might be necessary

Operation

- Electricity for water pumping, cleaning, etc.
- Chemicals for cleaning
- Back flush (if membrane can be backwashed)

Maintenance

- Periodical cleaning of the membranes to prevent membrane blocking
- Regular maintenance of pre-treatment unit (if needed for membrane operation)

Connecting NBS units

- Treatment wetland (NBS 21)
- Algal photobioreactors (NBS 48)
- Anaerobic treatment (NBS 26)
- Aerobic (post) treatment (NBS 27)

Connecting NBS supporting units

- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)

OUTPUTS

Type of outgoing streams

- Effluent water with quality that can be tailored by the type of membrane used and enabling water reuse: "fit for use" depending on end user needs
- Concentrate stream (brine) with accumulated compounds that do not pass through the membrane. Brine streams treatment and/or the possibility to reduce the liquid stream by e.g. crystallization => zero-liquid discharge)

Co-benefits and limitations

- Effluent is solid free and of high-quality enabling water reuse
- Effluent is pathogen free in case of UF, NF and RO
- Small footprint
- Relatively High energy use

Risks

- Concentrated stream needs to be handled

Connecting NBS units

- Street trees (NBS 39)
- Large urban park (NBS 40)
- Pocket/garden park (NBS 41)
- Productive Garden (NBS 49)
- Urban forest (NBS 50)

Connecting NBS supporting units

- Disinfection (SU 5)
- Membrane filtration (SU 8)
- Adsorption (SU 9)
- Advanced oxidation (SU 10)

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BIOLOGICALLY ACTIVATED CARBON (BAC) TREATMENT / ACTIVATED CARBON (AC) ADSORPTION (SU 9)

INPUTS

Construction

- Concrete or metallic filter
- Inflow and outflow pipes (and pumps)
- Granular activated carbon

Type of incoming streams

- Polluted water

Operation

- Filter backwashing

Maintenance

- Substitution of exhausted activated carbon

Connecting NBS units

- Treatment wetland (NBS 21)
- Waste stabilisation pond (NBS 22)
- Aerobic (post)treatment (NBS 27)

Connecting NBS supporting units

- Rainwater harvesting (SU 1)
- Phosphate precipitation (SU 3)
- Ammonia stripping (SU 4)
- Disinfection (SU 5)
- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)

OUTPUTS

Type of outgoing streams

- Activated carbon (material recovery and reuse; a material with adsorption capacity, active free valances, high surface area, porous structure, surface reactivity, inertness, and thermal stability that provides a large surface area to which may adsorb so it is used as filter matrix)
- Effluent

Co-benefits and limitations

- C-rich material reuse
- Carbon sequestration

Risks

- -

Connecting NBS units

- Street trees (NBS 39)
- Large urban park (NBS 40)
- Pocket/garden park (NBS 41)

Connecting NBS supporting units

- Disinfection (SU 5)

FURTHER READINGS

- Pharmafilter (includes ozone) https://pharmafilter.nl/en/
- VUNA-system for Aurin production https://vuna.ch/en/
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ADVANCED OXIDATION PROCESSES (AOPs) (SU 10)

INPUTS

Construction

- Tanks (reactors for the AOP processes)

- Pumps
- Generator of ozone and hydrogen-peroxide

Type of incoming streams

- Treated grey water
- Influent with low organic matter content

Operation

- Chemicals ($FeSO_4$, H_2O_2, etc)
- UV source
- Catalyst
- TiO_2
- Mixing

Maintenance

- Monitoring of COD, pH, temperature
- Replacing UV lamps

Connecting NBS units

- -

Connecting NBS supporting units

- Solid/liquid separation (SU 7)
- Membrane filtration (SU 8)
  Biologically activated carbon (BAC) treatment / activated carbon (AC) adsorption (SU 9)

OUTPUTS

Type of outgoing streams

- Check presence of undesired byproducts
- Material waste – exhausted catalysts (if we choose to use photocatalysis)

Co-benefits and limitations

- Removal of pathogens
- Highly treated wastewater (high quality effluent)
- Removal of xenobiotics
- Removal of non-biodegradable and highly toxic compounds

Risks

- Unwanted by-products (insufficient treatment of some non-biodegradable organic materials

Connecting NBS units

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Connecting NBS supporting units

Biologically activated carbon (BAC) treatment / activated carbon (AC) adsorption (SU 9)

FURTHER READINGS

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