Blue-Green Systems

© 2020 The Authors
138

Blue-Green Systems Vol 2 No 1
doi: 10.2166/bgs.2020.930

A review of nature-based solutions for resource recovery in cities

Johannes Kisser[a,*], Maria Wirth[a], Bart De Gusseme[b,c], Miriam Van Eekert[d,e], Grietje Zeeman[e], Andreas Schoenborn[f], Björn Vinnerås[g], David C. Finger[h], Sabina Kolbl Repinc[i], Tjaša Griessler Bulc[j], Aida Bani[k], Dolja Pavlova[l], Lucian C. Staicu[m], Merve Atasoy[n], Zeynep Cetecioglu[n], Marika Kokko[o], Berat Z. Haznedaroglu[p], Joachim Hansen[q], Darja Istenič[r], Eriona Canga[s], Simos Malamis[t], Margaret Camilleri-Fenech[u] and Luke Beesley[v]

[a] alchemia-nova GmbH, Institute for Innovative Phytochemistry & Closed Loop Processes, Vienna, Austria

[b] FARYS, Production & Transport TMVW, Gent, Belgium

[c] Center for Microbial Ecology and Technology, Ghent University, Gent, Belgium

[d] Environmental Technology, Wageningen University, Wageningen, The Netherlands

[e] LeAF BV, Bornse Weilanden, Wageningen, The Netherlands

[f] Institute of Natural Resources Science, Zurich University of Applied Science, Waedenswil, Switzerland

[g] Department of Energy & Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden

[h] School of Science and Engineering, Reykjavik University, Reykjavik, Iceland

[i] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia

[j] Faculty of Health Sciences, University of Ljubljana, Ljubljana, Slovenia

[k] Agro-Environmental Department, Faculty of Agronomy and Environment, Agricultural University of Tirana, Tirana, Albania

[l] Department of Botany, Faculty of Biology, University of Sofia, Sofia, Bulgaria

[m] Faculty of Biology, University of Warsaw, Warsaw, Poland

[n] Department of Chemical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

[o] Faculty of Engineering and Natural Sciences, Tampere University, Tampere, Finland

[p] Institute of Environmental Sciences, Bogazici University, Bebek, Istanbul, Turkey

[q] Chair for Urban Water Management, University of Luxembourg, Luxembourg, Luxembourg

[r] Faculty of Health Sciences, University of Ljubljana, Ljubljana, Slovenia

[s] Department of Environment, Faculty of Urban Planning and Environmental Management, POLIS University, Tirana, Albania

[t] Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Zografou Campus, Athens, Greece

[u] Institute for Climate Change and Sustainable Development, University of Malta, Msida, Malta

[v] The James Hutton Institute, Craigiebuckler, Aberdeen, Scotland, UK

*Corresponding author. E-mail: jk@alchemia-nova.net

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Blue-Green Systems Vol 2 No 1
doi: 10.2166/bgs.2020.930

Abstract

Our modern cities are resource sinks designed on the current linear economic model which recovers very little of the original input. As the current model is not sustainable, a viable solution is to recover and reuse parts of the input. In this context, resource recovery using nature-based solutions (NBS) is gaining popularity worldwide. In this specific review, we focus on NBS as technologies that bring nature into cities and those that are derived from nature, using (micro)organisms as principal agents, provided they enable resource recovery. The findings presented in this work are based on an extensive literature review, as well as on original results of recent innovation projects across Europe. The case studies were collected by participants of the *COST Action Circular City*, which includes a portfolio of more than 92 projects. The present review article focuses on urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, the recoverable products (e.g., nutrients, nanoparticles, energy), as well as the implications of source separation and circularity by design. The analysis also includes assessment of the maturity of different technologies (technology readiness level) and the barriers that need to be overcome to accelerate the transition to resilient, self-sustainable cities of the future.

Key words: circular cities, energy, nature-based solutions, nutrients, resource recovery

ABBREVIATIONS/ACRONYMS

AD	Anaerobic digestion
ALE	Alginate-like exopolysaccharides
ATAD	Autothermal thermophilic aerobic digestion
Bio-W	Bio-waste
BIQ	Bio-intelligent quotient
BOD	Biological oxygen demand
BW	Blackwater
CDW	Construction and demolition waste
COD	Chemical oxygen demand
CSTR	Continuously stirred tank reactor
CW	Constructed wetland
DTM	Dry toilet matter
ESCO	Energy service companies
EWS	Evapotranspirative willow system
FGD	Flue gas desulphurisation
FW	Food waste
GHG	Greenhouse gas
GDP	Gross domestic product
GrW	Green waste
GW	Greywater
HRAP	High-rate algal ponds
K	Potassium
LCFA	Long-chain fatty acids
MBR	Membrane bioreactor
MBT	Mechanical biological treatment
MFCs	Microbial fuel cells
MSW	Municipal solid waste
N	Nitrogen
NBS	Nature-based solutions
OLAND	Oxygen-limited autotrophic nitrification/denitrification
P	Phosphorus
PBR	Photobioreactor
PCB	Polychlorinated biphenyl
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PPB	Purple phototrophic bacteria
R&D	Research and development
RO	Reverse osmosis
TRL	Technology readiness levels

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

TS	Total solids
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
VFAs	Volatile fatty acids
VFY	Vegetable, fruit and yard waste
VSS	Volatile suspended solids
WW	Wastewater
WWTP	Wastewater treatment plant
YW	Yellow water

INTRODUCTION

Cities are emerging as centres of human and economic capacity, with 54% of the global population living in cities and raising 85% of worldwide GDP (World Bank 2017). However, cities also accumulate or emit end-user resources and wastewater, functioning as resource sinks within the current linear economic model of 'take-make-dispose'. Urban populations consume 75% of natural resources, they are responsible for 50% of global waste and for 60–80% of overall greenhouse gas emissions (Ellen MacArthur Foundation 2017). Given the human and economic potential, the accumulation of resources and societal challenges of ecosystem degradation present in urban areas, the momentum is shifting towards recovery of these resources within the urban infrastructure.

Resource flows are generally considered 'waste', destined for final disposal as soon as they reach sewage systems, rubbish bins and exhaust pipes, although they include valuable resources such as nutrients (N, P, K), organics, water and metals. Each year, Europeans produce 3.6 Mt of N, 1.7 Mt of P and 1.3 Mt of K as part of human excrement. At the same time, Europe consumes 11 Mt of N, 2.9 Mt of P and 2.5 Mt of K of manufactured fertilisers (Fertilizers Europe 2017). The volumes of post-use material bear high potential. Therefore, the present study considers secondary resource streams, including urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, as well as the potential of source-separated waste(water) streams. Figure 1 showcases the urban water, nutrient, material and energy loops established by using and integrating nature-based solutions (NBS) in cities.

The present paper is a product of interdisciplinary cooperation among researchers from all 28 EU countries and 11 third countries within the EU-funded *COST Action Circular City*. Discussions among project members have produced a definition of nature-based solutions for the purpose of the COST Action, set out in Langergraber *et al.* (2019). As such, the present paper defines NBS as technologies that bring nature into cities and those that are derived from nature, using *organisms as principal agents* if they enable resource recovery and the restoration of ecosystem services in urban areas. The objective of this review is to provide a comprehensive overview of NBS applied and developed today to recover resources in cities, along current cutting-edge research and innovation, and to map out recoverable products as well as barriers, which represent the scope for further research. NBS can be applied to micro (household), meso (district) and macro (city and above) scales (Langergraber *et al.* 2019).

The findings are based on a literature review, as well as on the review of ongoing and recent research and innovation projects. These case studies were collected by participants of the *COST Action Circular City* with a portfolio of a total 92 research projects, as well as projects that partner researchers are aware of. Case studies specifically mentioned in the paper illustrate the diversity of applications and recoverable products. Based on discussions within the Action's working group on *resource recovery*, the present review paper looks at urban wastewater, industrial wastewater, municipal solid waste and gaseous effluents, as well as the implications of source separation of waste and end-of-pipe technologies versus circularity by design. Non-technical interrelated factors, which influence the applicability, selection and adoption of available technologies, such as legal frameworks, community awareness, acceptance and involvement, business and financing conditions, are not addressed here but are discussed in a separate review paper (Katsou *et al.* 2019).

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Blue-Green Systems Vol 2 No 1
doi: 10.2166/bgs.2020.930

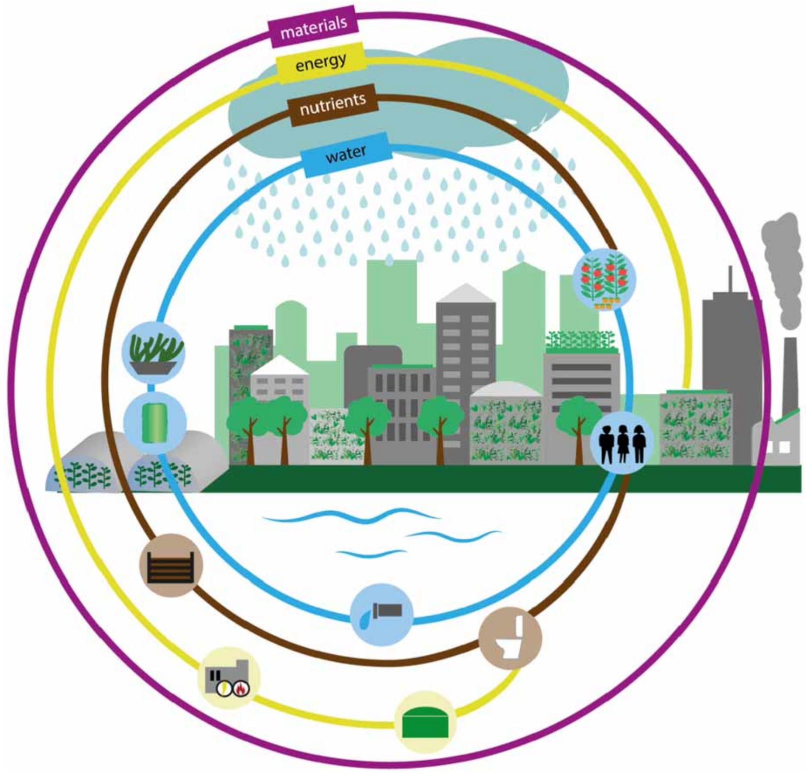

Figure 1 | Overview of urban water, nutrient, material and energy loops enabled using NBS within cities.

RESOURCE STREAMS AND OPPORTUNITIES FOR RECOVERY IN CITIES

The following section reviews different secondary resource streams found in cities, subdivided in urban wastewater, industrial waste and wastewater, municipal solid waste, gaseous effluents and source-separated waste. It provides an overview of technologies, projects and developments as well as barriers in relation to resource recovery with NBS.

Urban wastewater

Urban wastewater is defined as domestic wastewater or its mixture with industrial wastewater and/or runoff rainwater (European Commission 1991). The adequate treatment of urban wastewater is essential to protect human health and the environment. In Europe, cities largely collect and treat urban wastewater as a mixture of grey and blackwater, often also stormwater (combined sewer system). In Europe, more than 277 million people live in agglomerations bigger than 150,000 population equivalent (PE). They produce 41.5 million m^3 of wastewater per day. Currently, an annual 2.4% (1 billion m^3) of treated urban wastewater effluents are reused in the EU (European Commission 2018b), but this secondary resource stream bears significantly more resources to recover, including nutrients, organic carbon, lipids, biosolids and energy. The vast majority is still unexploited, but many of these can be recovered in cities using NBS. Table 1 provides an overview of projects deriving secondary resources and products from unsegregated urban wastewater, including reclaimed fertigation/irrigation water (water and nutrients), P-rich sludge, biopolymers, alginates, cellulose, construction material and energy (biogas, biofuel, electricity and heat). Information on the scale at which the technology is applied, the technology readiness level (TRL), region, project and project periods provide an indication as to the transferability of applied technologies.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 1 | Overview of resources that can be recovered from unsegregated urban wastewater, recovery technologies applied, recovered products, scale, TRL, region and project

Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Reclaimed water, energy and nutrients	Upflow anaerobic sludge blanket (UASB) + constructed wetlands + UV disinfection	Fertigation water; domestic non-potable water	Micro, meso	7	Lesvos Island, Greece	HYDROUSA	2018–2022	https://www.hydrousa.org/
	Combination with shred kitchen waste, liquid-solid separation, green walls, anaerobic membrane bioreactor (AnMBR), UV hygienisation	Fertigation water; biogas, fertiliser, domestic non-potable water	Micro	7	Austria, Spain	HOUSEFUL	2018–2022	https://houseful.eu/
	Hybrid constructed wetland, evapotranspirative willow system with zero discharge, algae-based technology	Fertigation water, woodchips for heat production	Micro, meso	7	Slovenia	GreenT (Slovenian Research Agency J2 – 8162 and Z2 – 6751)	2017–2020	http://www2.zf.uni-lj.si/si/component/content/article/32-raziskovanje-splosno/2489-zapiranje-snovnih-poti-pri-ciscenju-komunalnih-odpadnih-voda-z-zelenimi-tehnologijami-j2-8162
Nutrients	Adsorption columns and planted filters	Nutrients for irrigation water	Micro	3–4	Barcelona and Almería, Spain	INCOVER	2019–2021	https://incover-project.eu/technologies/nutrient-recovery
Organic carbon (carbohydrates)	Two-stage anaerobic-photosynthetic high-rate algal pond system	Biopolymers	Micro	6	Chiclana de la Frontera and Almería, Spain	INCOVER	2019–2021	https://incover-project.eu/technologies
	Two sequencing batch reactors (SBR): one for heterotrophic bacterial growth and the other for growth of autotrophic nitrifiers	Biopolymers (PHA) and P-rich sludge	Macro	6	Manresa, Spain	SMART-Plant	2016–2019	http://www.smart-plant.eu/
	Mixed microbial cultures, activated sludge at WWTP, bioprocess facilitating feast and famine conditions, biomass is fed with VFA-rich liquors, pure acetic and propionic acids	Biopolymers (PHA)	Meso	6–7	The Netherlands	Phario	2015–2019	http://phario.eu/
	Alginate extraction from granular excess sludge from 3 municipal Nereda®-plants and one industrial one	Alginates	Macro	6	WWTP Epe, Dinxperlo, Vroomshoop, The Netherlands	National Alginate Research Programme	2013–2019	https://www.royalhaskoningdhv.com/en-gb/news-room/news/water-authorities-working-hard-to-achieve-circular-economy/7123
	Alginate extraction from Nereda®-granular excess sludge	Kaumera Nereda® Gum (formerly: Neoalginate)	Macro	7–8	WWTP Zuthpen, The Netherlands	KAUMERA	2016–2018	https://kaumera.com/english/
Lipids	Two-stage aerobic/anaerobic reactor, *M. parvicella* bacterium accumulates FOG (fat, oil, grease), lipids extraction, subsequent esterification/transesterification	Biofuel	Micro	3–4	Luxembourg & France	WOW	2018–2021	https://www.cell-vation.com/wow-project

(*Continued*)

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 1 | Continued

Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Energy, nutrients	Anaerobic biofilter for municipal wastewater treatment	Biogas	Meso, macro	7	Karmiel, Israel	SMART-Plant	2018–2020	http://www.smart-plant.eu/
	UASB for municipal wastewater	Biogas	Meso	7	Sweden	Pioneer-STP	2016–2019	https://www.kt.dtu.dk/english/research/prosys/projects/pioneer-stp
	Vacuum toilets and collection, AD, Fixed bed reactor, heat exchange, district heating	Biogas, fertiliser, thermal energy	Meso	7–8	Hamburg, Germany	Hamburg Water Cycle, Jenfelder Au	2011–2018	https://www.hamburgwatercycle.de/en/the-jenfelder-au-neighbourhood/the-hwc-in-the-jenfelder-au/
Energy	Horizontal subsurface CW with electrodes; oxidation of the organic matter generates electricity	Electricity	Micro	4–5	Spain, UK, Turkey	URBAN GreenUP	2017–2022	https://www.urbangreenup.eu/
Energy, salts	Microbial desalination combined with membrane treatment	Freshwater, treated wastewater	Micro, meso	5	Spain, Chile, Tunisia	MIDES	2016–2020	http://midesh2020.eu/
Nutrients, lipids, cellulose	Microbial conversion of nutrients to high-value compounds in a biorefinery approach	Ectoine, PHA, biogas, cellulose, construction materials	Meso, macro	6	Spain	DEEP PURPLE	2019–2023	https://deep-purple.eu/

DEEP PURPLE: Conversion of diluted mixed urban bio-wastes into sustainable materials and products in flexible purple photobiorefineries. GreenT: Closure of material pathways in urban wastewater treatment with green technologies. HYDROUSA: Demonstration of water loops with innovative regenerative business models for the Mediterranean region. INCOVER: Innovative eco-technologies for resource recovery from wastewater. MIDES: Microbial desalination for low energy drinking water. Pioneer-STP: The potential of innovative technologies to improve sustainability of sewage treatment plants. Run4Life: Large-scale nutrient recovery from domestic wastewater. SMART-Plant: Scale-up of low-carbon footprint material recovery techniques in existing wastewater treatment PLANTs. WOW: Wider business opportunities for raw materials from wastewater.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Technologies and products

As set out in Table 1, NBS for resource recovery from urban wastewater range from extensive technologies, such as constructed wetlands, evapotranspirative willow systems and algae ponds, to high-tech biological processes, such as rotating biological contactors, aerobic granulation (Nereda$^{®}$) and anaerobic reactors. The wide range of recoverable products includes commonly derived products, such as biogas from primary and secondary sludge and reclaimed water for agricultural (crop irrigation or fertigation), industrial (cooling water), residential (sanitary flushing) and urban (park irrigation or even crop production) purposes as well as for groundwater recharge.

Combustible biomass of plants and microalgae can be converted to biogas and digestate for use as fertiliser through anaerobic digestion, bioethanol through sugar fermentation or ethylene reaction with steam (EUBIA 2019), biochar through pyrolysis, or processed for pulp-paper production or bioplastics. Bio-oil is produced by processing biomass under high temperature without oxygen and biohydrogen by steam reformation of bio-oils, dark and photofermentation of organic material as well as photolysis of water catalysed by specific microalgae species (Li *et al.* 2008). Algae biomass can also be used for feed production and extraction of high-value chemicals (Razzak *et al.* 2013; Passos *et al.* 2014; Wuang *et al.* 2016; Fermoso *et al.* 2019).

Constructed wetlands and nutrient-rich irrigation. Urban wastewater contains nitrogen and phosphorus which is usually not valorised within wastewater treatment plants (WWTPs). Although raw urban wastewater is a diluted effluent with low concentrations of nitrogen (30–70 mgN/L) and phosphorus (5–12 mgP/L), the large flows of generated wastewater carry significant quantities of nutrients. Constructed wetlands (CW) are the most common extensive NBS for nutrient recovery. They offer effective, reliable, robust and low-cost treatment of wastewater. Moreover, the nutrient content in the outflow can be adapted to the needs for crop fertigation. They can be integrated with other engineered solutions, such as anaerobic processes to meet strict water reuse regulations.

The EU-funded *HYDROUSA* project (Table 1) combines upflow anaerobic sludge blanket (UASB) with vertical constructed wetlands and UV disinfection to treat domestic sewage. The treated effluent is rich in nutrients, but has very low chemical oxygen demand (COD) and total suspended solids (TSS) levels, and is free of pathogens. It is used at the demonstration site to develop an agroforestry unit on the arid island of Lesvos, Greece, thereby reusing nutrients directly for agricultural purposes. The *HOUSEFUL* project (Table 1) also utilises domestic wastewater directly on site. It diverts the solids and liquids of the unsegregated household wastewater and treats the liquid fraction in green walls, hygenises it with UV radiation and reuses it for flushing toilets and irrigating food crops in greenhouses. The solids are co-digested together with the organic household waste in small biogas plants. The digested matter is converted to compost in a closed-vessel composting unit with in-built odour abatement (Bertino *et al.* 2018).

Numerous laboratory-scale experiments have been conducted introducing electrodes to (constructed) wetlands (e.g., iMETland or plant-e projects), generating electricity from the oxidation of the organic matter, but only a few pilot facilities have been attempted. The *URBAN GreenUP* project (Table 1) is piloting horizontal sub-surface flow (HSSF) wetlands, where electrodes and electrical connections through the filter bed stimulate the growth of an exoelectrogenic biofilm able to transfer the electrons generated by decomposition of organic matter. The *MIDES* project (Table 1) combines urban wastewater treatment and desalination by using microbial desalination processes to generate energy and run conventional reverse osmosis with the generated electricity.

The evapotranspirative willow system (EWS) (GreenT, see Table 1) treats wastewater and produces wood biomass. Mechanically pre-treated municipal wastewater flows into a waterproof bed filled with soil and planted with selected willow clones. In two research projects funded by the Slovenian Research Agency, willows in this system have been found to produce significantly more biomass

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

compared to control trees, namely 34–38 t DM/ha (Istenič *et al.* 2017, 2018). The treatment of wastewater produced by one person in a sub-Mediterranean climate requires 42 m^2 of EWS and produces 140–179 kg of wood biomass per year. Where available space allows the application of EWS, the wood biomass produced can be used for heating houses.

Microbial biotechnology. Anaerobic digestion is a popular treatment method for wastewater treatment sludge and enables recovery of energy (biogas, electricity, heat) and nutrients. Significant research is being conducted to enhance biogas and energy yields as well as valorisation of value-added products from side streams (intermediate products and valorisation of digestate). Among the projects mentioned in Table 1, *HYDROUSA, HOUSEFUL, SMART-Plant, Pioneer-STP* and *Hamburg Water Cycle/Jenfelder Au* are applying biomethane production using technologies such as common anaerobic digester, upflow anaerobic sludge blanket, anaerobic membrane bioreactor, anaerobic biofilter. Recently, biological production and harvesting of N_2O gas for energy recovery and reduction of high nitrogen loads in digestate centrate was performed by coupled aerobic-anoxic nitrous decomposition operation (CANDO). Combustion of N_2O with biogas increases energy yields and reduces the emission of the potent greenhouse gas (Weißbach *et al.* 2018).

Biofuel is usually produced from vegetable oils (soybean, canola, sunflower, palm and coconut oils) and animal fats, requiring large amounts of agricultural land. Urban wastewater can provide large quantities of alternative lipid feedstocks that help to meet the increasing demand for biofuel but do not compete with food production. Lipids, including oils, greases, fats and long-chain fatty acids are significant organic components of municipal wastewater, accounting for approximately 30–40% of the total COD of 120 g per PE and day, which means that about 18 kg per PE and year can be found in raw wastewater (Chipasa & Mędrzycka 2006). In the EU-funded WOW project (Table 1), lipids are accumulated by *Microthrix parvicella* bacteria and then processed to biofuel. The filamentous, selective lipid accumulator also has the ability to take up long-chain fatty acids, which can be used directly for the production of biofuel (Uwizeye *et al.* 2017).

The Nereda® process is a wastewater treatment technology, where activated sludge forms granules that have the ability to settle very fast. From these sludge granules, so-called 'alginate-like biopolymers' or 'alginate-like exopolysaccharides (ALE/Kaumera)' as a raw material can be obtained (Van der Roest *et al.* 2015). Aerobic granular sludge from the Nereda® process contains about 15–25% ALE that can be recovered. This material has the ability to bind strongly with water, can thicken and can also be used as a basis for coatings. The wastewater-derived alginate could be used for manifold applications, e.g., in the medical and food industries (Van der Roest *et al.* 2015). The neoalginate is already being recovered from granular sludge in three municipal WWTPs and one industrial plant in the Netherlands. The Zutphen WWTP produces 'Kaumera Nereda® Gum' (biopolymers), which can both retain and repel water. It is useful for a wide range of applications, e.g., in agriculture, to reduce leaching of fertilisers and enhance crop nutrient uptake, and in the concrete industry as a water-repellent coating for concrete floors (Waterschap Rijn en IJssel 2018).

Purple phototrophic bacteria (PPB) can convert organic matter from wastewater and from the organic fraction of municipal solid waste (MSW) into high-value compounds. Within the *DEEP PURPLE* project (Table 1), a PPB photobiorefinery is developed combining biomass, cellulose and biogas production in one single site. PPB uses near-infrared light as the main energy source, so they do not compete with other phototrophs such as microalgae or cyanobacteria (Madigan & Jung 2009).

Polyhydroxyalkanoates (PHAs) are bio-based and biodegradable thermoplastic polyesters. They are produced mostly from sugars or fats with pure culture fermentation. The *Phario* project (Table 1) is piloting a different approach, where secondary sludge from a municipal sewage treatment plant provides the functional biomass to produce PHA. Organic residues from the surrounding region were

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

collected, fermented and successively fed to the sludge to produce a PHA-rich biomass with PHA content of 40–50% of the total volatile suspended solids (VSS). This PHA-rich biomass was acidified, dewatered by centrifugation and dried in a thermal dryer. The facility uses solvents such as butanol, which are reused (Bengtsson *et al.* 2017). The preliminary investigation was conducted in a pilot-scale facility in Brussels, using the full-scale secondary activated sludge from Bath WWTP (500,000 PE). The pilot has produced a biomass with PHA content of up to 0.47 g PHA/g VSS, which is above the considered profitability threshold (0.40 g PHA/g VSS) (Bengtsson *et al.* 2017). Each year, 2,000–2,500 t PHA can be produced from 2,500 t VSS of waste activated sludge generated in Bath WWTP. The results show that the harvested activated sludge could consistently yield PHA with high and controllable quality with fewer process elements, lower manufacturing costs and significantly lower environmental impact compared to currently available bioplastics.

Barriers

Reclaimed water and its treatment products can pose environmental, health and safety risks, which must be addressed during the development of resource recovery and water reuse systems. The products may contain pollutants and micropollutants like heavy metals, pharmaceuticals, personal care products, industrial chemicals, pesticides, microplastics, etc., which may enter the food chain through application to agricultural land. NBS can remove micropollutants often more effectively than conventional WWTPs (Guenther *et al.* 2002; Kabir *et al.* 2015; Gattringer *et al.* 2016; Balabanič *et al.* 2017), as conventional WWTPs are not designed to remove them. Due to their potential oestrogenic, mutagenic and carcinogenic activity (World Health Organization 2011), their removal and fate in NBS is of interest for the purpose of wastewater reuse and reclamation of other derived products.

An often-cited key barrier to the adoption of extensive technologies in densely populated areas (CW, algae systems and EWS) is the surface area requirement. However, microbial fuel cell technologies, active/passive aeration and innovative structural set-ups (e.g., vertECO® (Zraunig *et al.* 2019)) are already making CWs applicable even to cities. Furthermore, unutilised and underutilised urban spaces (including rooftops, facades, indoor spaces) could be used for nature-based urban wastewater treatment, resource reclamation and additional benefits, such as biodiversity, climate change mitigation and aesthetic/regenerative effects for the population. In order to facilitate the uptake of innovative rooftop and facade solutions, more demonstration projects are needed, to prove their functionality at relevant scales and a higher variety of contexts.

For research and non-research installations, the lack of standards, existing legal frameworks and lack of awareness of public administrative bodies make it very difficult to obtain building permits for these non-conventional systems. Authorities stick to existing laws and specific articles also for research purposes, as existing legal frameworks mostly do not include an exception for research. In the Netherlands, so-called Green Deals create a testing space for innovations for a certain timeframe (Rijksdienst voor Ondernemend Nederland 2019).

Further, the high number of derived end-products can result in competition between themselves, e.g., if lipids are extracted for biofuel production, the potential for biogas production is reduced. Practitioners and public entities often lack the know-how to identify the optimal biorefinery design and choice of secondary products in their individual cases. This calls for increased knowledge sharing for the available possibilities and selection parameters, including technical factors as well as economic factors (supply, demand, production costs, prices). Finally, some of the mentioned technologies have yet to mature in terms of technical readiness, the enabling legal and market framework, production costs and value chain as well as comprehensive impact assessments before they can be widely applied.

Industrial waste and industrial wastewater. Several raw and intermediate materials can be recovered from industrial waste streams using NBS. Studies at various scales exist for the recovery

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

of energy, carbon, nutrients, metals and chemicals from wastewater of pharmaceutical, chemical, food processing and metal industries (Mansouri *et al.* 2017; O'Dwyer *et al.* 2018; Song *et al.* 2018; Diaz-Elsayed *et al.* 2019). Table 2 gives an overview of recent and ongoing research projects recovering secondary resources and products from waste incineration as well as metal, dairy, food and pulp and paper industrial plants in cities.

Technologies and products

Phytomining. Phytomining is a 'green' alternative to opencast mining practices (Chaney *et al.* 2007) often causing environmental pollution. It is applied to recover a range of metals (Ni, Co, Au) but most often is used for Ni production in abandoned ferronickel mining sites (Osmani & Bani 2017; Osmani *et al.* 2018a, 2018b) and in naturally metalliferous soils (Li *et al.* 2003; Bani *et al.* 2015, 2018) because this raw material has gained high economic importance. The Ni-agromining chain consists of two stages: (1) the cultivation of hyperaccumulator plants to obtain sufficient aerial biomass with a high Ni concentration and (2) the transformation of the biomass to obtain valuable end-products. Both *in-situ* and *ex-situ* experiments were carried out in Albania, Spain, Austria and Greece, and Ni has been successfully recovered from bio-ores in pure form, as a mineral salt (ammonium nickel sulphate hexahydrate) or as eco-catalysts (Simonnot *et al.* 2018).

Using phytomining technology, the resulting ash is a real bio-ore, containing up to 20 weight percentages of Ni. It is possible to obtain different Ni compounds (e.g., Ni metal, Ni-based catalysts, Ni salts as ammonium nickel sulphate hexahydrate or oxides) by hydrometallurgical processes, where washing and refining processes are involved (Zhang *et al.* 2016; Houzelot *et al.* 2017, 2018). The cost of Ni is determined by the cost of the subsequent pyro- or hydrometallurgical processes. The production of Ni compounds such as ammonium nickel sulphate hexahydrate is a better alternative for Ni metal production, because of the higher price (97.50 EUR for 500 g with 98% purity, and 134 EUR for 25 g with 99.999% purity (Sigma-Aldrich 2018)).

Constructed wetlands. The food industry produces highly nutrient-rich solid waste and wastewater, which is a large untapped nutrient source. The *HIGHWET* project (Table 2) demonstrated constructed wetlands with reduced area successfully treating wastewater from food processing plants in Spain, Denmark and Belgium. The biomass can be processed to products mentioned above (in the section 'Urban wastewater').

Microbial biotechnology. Microbial biotechnology offers the advantage of using natural, high-affinity enzymes of different microorganisms that preferentially target the substrate of interest present in the industrial effluent (e.g., soluble selenium and other chemical elements, organic acids) to produce desirable end-products of industrial relevance (e.g., nanoparticles, biogas, biofuel). Examples of microbial technologies at microscale include Se nanoparticle recovery from waste streams of coal-fired power plants, bioelectrochemical metal recovery from metal and mining industry wastewaters, anaerobic digestion of dairy industry wastewaters for biogas production, fermentation of dairy or pulp and paper industry wastewaters for production of volatile fatty acids (VFAs) and/or hydrogen, and conversion of methanol in pulp industry wastewaters to VFAs with acetogenesis (Table 2).

Se is an essential micronutrient and a critical raw material with wide-range industrial utilisation (Hennebel *et al.* 2015). The current production of Se involves energy-intensive pyrometallurgical processing and smelting of Cu and Pb-ores, where it is recovered as an impurity. As a solution to its scarcity, Se could be recovered from industrial, secondary resources, such as effluents of flue gas desulphurisation (FGD), using cost-effective and environmental-friendly biotechnological approaches (Cordoba & Staicu 2018). Various bacterial groups can metabolise Se to generate cellular energy (i.e.,

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 2 | Overview of recoverable resources from industrial waste and wastewater streams in cities, by secondary resource stream, recoverable resource, technologies applied, products, scale, TRL, region and project

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Bottom ash from incinerated MSW	Metals	Bioleaching	Enriched solution, Ga, Co, Mg, Cu, Zn, Al, Cr	Micro	3–4	Austria	GrecoMet	2016–2019	https://www.alchemia-nova.net/projects/grecomet/
Metal industry contaminated soil		Agromining	Nickel salt	Meso	6	Mediterranean climate	Life AgroMine	2016–2020	https://life-agromine.com/en/homepage/
Metal industry WW	Selenium, nanoparticles	Bioremediation coupled with resource recovery	Selenium nanoparticles	Micro	3–4	Temperate climate	Selenex	2018–2021	http://ddg.biol.uw.edu.pl/projects/staicu-sonata/
	Metals	Microbial fuel cell	Copper	Micro	3–4	The Netherlands, UK, Sweden, Finland, Spain, Luxembourg	BioElectroMET	2012–2016	http://www.bioelectromet.eu/
Dairy industry WW	Carbohydrates	Fermenter-bioaugmentation	VFAs	Micro	3–4	Sweden	EnVFAPro	2017–2018	https://www.kth.se/sv/ket/resource-recovery/envfapro-1.703273
	Energy	Anaerobic digestion	Methane	Micro	3–4	Denmark	ABWET	2015–2018	http://www.internationaldoctorate.unicas.it/abwet/
Food industry	Wastewater	Constructed wetland	Nutrient-rich biomass, clean water	Micro	5	Spain, Denmark, Belgium	HIGHWET	2013–2015	http://www.highwet.eu/
Pulp industry craft mill foul condensate	Organic carbon	Acetogenesis (anaerobic digestion)	VFAs	Micro	3–4	Italy	ABWET	2015–2018	http://www.internationaldoctorate.unicas.it/abwet/
Pulp and paper industry WW	Carbohydrates	Dark fermentation	Hydrogen, VFAs	Micro	3–4	Italy	ABWET	2015–2018	http://www.internationaldoctorate.unicas.it/abwet/

ABWET: Advanced biological waste-to-energy technologies. EnVFAPro: Enhancement of volatile fatty acid production from dairy wastewater. GrecoMet: Green recovery of metals. HIGHWET: Performance and validation of HIGH-rate constructed WETlands. Selenex: Harvesting resources from industrial streams.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

ATP) through anaerobic respiration, in parallel with the production of solid Se nanoparticles (Ni *et al.* 2015), as displayed in Figure 2.

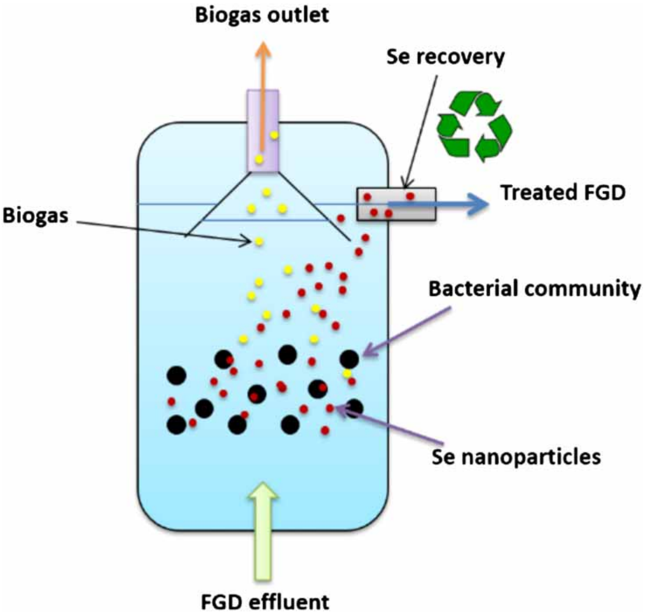

Figure 2 | Biological treatment and recovery of selenium using a biotechnological approach (modified from Cordoba & Staicu 2018).

Copper recovery from metallurgical waste and process streams using microbial fuel cells (MFCs) has been demonstrated. In MFCs, bacteria act as biocatalysts at the anode and generate current by oxidation of organic or inorganic substrates. The current can be used at the cathode to reduce, e.g., metal ions to solid metal species. Biological oxidation of either acetate (Rodenas Motos *et al.* 2015) or tetrathionate (Sulonen *et al.* 2018) has been coupled to Cu recovery in laboratory-scale MFCs. Furthermore, an MFC coupling acetate oxidation to Cu recovery was scaled-up to bio-anode and cathode surface areas of 835 cm^2 and 700 cm^2, respectively (Rodenas Motos *et al.* 2017).

Dairy industry wastewater contains high amounts of biodegradable carbon (Slavov 2017) and is a great source for the production of VFAs, which are valuable intermediate products of anaerobic digestion used in the conventional chemical industry. VFA on the market include formic, acetic, propionic, butyric, valeric and caproic acid. VFA have a wide range of applications, their recovery generates high production yield and releases less GHG emissions than biogas production (Atasoy *et al.* 2018). Bioaugmentation of the mixed cultures with pure *Clostridium aceticum* cultures proved to increase acetic acid production by 96 times, bioaugmentation with *C. butyricum* increased butyric acid production 120 times and *Propionibacterium acidipropionici* increased propionic acid production around five times compared to the control experiments. This case study (EnVFAPro project, Table 2) has shown that bio-based VFA production from waste streams can be environmentally friendly and economically feasible.

A pilot study (*HIGHWET* project, Table 2) at industrial food processing plants in Spain and Denmark tested the effect of effluent recirculation, aeration regime and different phosphorus adsorbent materials in a system that combines a hydrolytic up-flow sludge bed (HUSB) anaerobic digester as primary treatment, hybrid (vertical and horizontal flow (VF-HF)) constructed wetlands (CWs) and two different phosphorus adsorbent materials for treatment of the wastewater characterised by high nutrient loads. The project achieved a decrease of the required surface of conventional HFCWs and improved the final effluent quality in the aerated and non-aerated line, but the aerated VFCW was able to treat a four times higher loading rate with similar treatment efficiency than the non-aerated VFCW (Pascual *et al.* 2018).

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Dairy wastewaters contain lipids that are hydrolysed into long-chain fatty acids (LCFA) that may be inhibitory to anaerobic microorganisms. Anaerobic conversion of LCFAs to methane was reported for the first time at 10 °C and 20 °C (with lipid content of >1%) in batch bottles, where the role of acetoclastic methanogens from the genus *Methanosaeta* was highlighted (Singh *et al.* 2019). In the pulp industry, recovery of chemicals from black liquor results in the production of condensates that contain methanol up to 46 g/L. The pulp industry also produces thermomechanical pulping wastewaters that are released at high temperatures (50–80 °C). Conversion of methanol from condensates to VFA has been reported with an acetogenic culture in an up-flow anaerobic sludge bed reactor (Eregowda *et al.* 2018). Thermomechanical pulping wastewater, on the other hand, has been anaerobically converted to hydrogen at 70 °C with a culture dominated by *Thermoanaerobacterium* sp. (Dessì *et al.* 2018).

A variety of products can be recovered using microbial technologies, depending on the type of waste stream and desired recovered product, including metals (Wang *et al.* 2019), nanoparticles (Goethem *et al.* 2018), VFA (Zacharof & Lovitt 2014) and renewable energy carriers such as biogas and biofuel. Among a wide variety of recovered products from industrial waste streams, the described products are most promising with their potential as a raw material for post-processing. Most of the described technologies are still being developed at laboratory and/or pilot scales (e.g., bioelectrochemical systems, VFA production) (Chen *et al.* 2017; Garcia-Aguirre *et al.* 2017; Jankowska *et al.* 2017), except biogas production, which is established and implemented at full scale (Mauky *et al.* 2017; Martí-Herrero *et al.* 2019). In addition to biogas, bioplastic production has also been applied at pilot scale (Tamis *et al.* 2018). Mo *et al.* (2018) used food waste, fish waste and food processing waste to produce fish feed through biotransformation and solid-state fermentation.

Barriers

The phytomining techno-economic model should be customised to country-specific data reflecting differences in soil physicochemical properties in relation to the phytomining system implemented, Ni concentrations in the soils, hyperaccumulator yields and metal prices. The process efficiency and Ni salt purity are the main challenges of phytomining. Process parameters such as stirring speed or reaction time can significantly influence efficiency and they should be thoroughly investigated to assess their influence at each step of phytomining. One of the main limitations of energy recovery is the combustion temperature. Previous experiments demonstrate that combining energy recovery and utilisation of ashes for Ni recovery are compatible if the combustion temperature is low enough to avoid Ni losses through fly ash or other outputs. Preliminary calculations for Ni phytomining show promising results under the condition that heat released during incineration can be valorised close to the processing facility.

The main limitations are related to the complex matrix of industrial effluents, which often contain toxicants, that limit or prohibit bacterial growth. To overcome these hurdles, the recovery systems need to employ mixed microbial communities (as opposed to pure bacterial cultures). These mixed communities offer the advantage of protecting the microbial species of interest (e.g., metal respires or methanogens) against the toxic environment of the industrial effluent. However, on the other side, mixed communities also result in competition between various bacterial groups, some having better fitness and thermodynamics than the ones of interest for resource recovery (e.g., more thermodynamically adapted sulphate-reducing bacteria vs methanogens or metal oxidisers) (Hoelzle *et al.* 2014; Cetecioglu *et al.* 2019; Tang *et al.* 2019).

Another major challenge is the large variation in the composition and/or volume of the wastewaters, which may result from varying feed material composition, periodic operation or production intermissions due to, e.g., maintenance and cleaning. In addition, although it is a promising approach to recover bio-based products from industrial and municipal wastewater, there are still some technical

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

challenges such as product recovery after anaerobic digestion and purity of the recovered products (Puyol *et al.* 2017; Atasoy *et al.* 2018). Therefore, the microbial technologies should be able to cope with these changes, where mixed microbial communities again are more resilient than pure cultures. To reach full-scale adaptation, the microbial technologies should thus be able to handle high organic loading rates, regarding also high nitrogen and phosphorous concentrations and ensure sufficient wastewater treatment and resource recovery/product spectrum at varying wastewater conditions. By scaling up these systems, broad communication with stakeholders is crucial for preparing the market with new bio-products such as VFA.

Finally, many of the technologies that enable recovery of products other than energy are still in development and applied so far only at laboratory and pilot scales. The next step for these technologies will be scale-up to demo and flagship scales. However, already at this stage, the communication with public and private stakeholders is essential to prepare the market, including legislative and regulatory framework for the new bio-products.

Municipal solid waste. According to the European Commission (2019), municipal solid waste (MSW) constitutes about 10% of total waste generated in the EU. Although this figure may not seem too excessive at first glance, MSW is extensively prevalent and requires complex management linked to the mixed composition and multiple points of collection, which require various treatment methods. MSW includes waste streams from households and similar wastes from commerce, offices, public institutions and selected municipal services, excluding municipal sewage and construction and demolition waste (CDW). NBS applied to recover a wide range of intermediate and final products from mixed or biodegradable MSW include composting, anaerobic digestion and mechanical biological treatment (MBT). Research has also been conducted on bioleaching from mixed MSW incineration ash. Table 3 gives an overview of recent and ongoing research projects recovering secondary resources and products from MSW streams.

Technologies and products

Resource recovery from mixed MSW. Mechanical biological treatment (MBT) can enable recovery of ferrous metal, non-ferrous metal, plastic and glass from mixed MSW, but is mainly applied to stabilise MSW before landfilling. The biological steps include anaerobic digestion, composting and biodrying. Where recycling and recovery activities are low, it can improve environmental and economic performance (Trulli *et al.* 2018). However, MBT achieves only lower quality recyclates compared to those derived from recyclables from separate household collection, and mostly only metals are extracted. Digestate derived from mixed MSW is generally reported to be of lower quality than from separately collected organic waste, largely due to contamination with, e.g., glass and potentially toxic elements such as heavy metals (EPEM S.A. 2011). Biodrying is a partial composting stage, where the action of aerobic microbes rapidly heats and dries the waste. This process is used to produce a refuse-derived fuel that is dry and light for transport (Bogner *et al.* 2007).

Mixed (residual) MSW is often incinerated for electricity and heat production, and the incineration ash landfilled. The GRecoMet project (Table 3) (alchemia-nova 2019b) applied *Acidithiobacillus* bacteria (among other trials) to recover metals (finally selecting Cu, Cd and partially Co) from MSW incineration ash. The diffusely dispersed metals are brought into solution through microbial leaching, a process that efficiently extracts metals even from low-grade ores, such as MSW incineration ash (Chemiereport.at 2017). In the next steps, for enrichment of the dissolved metals, different NBS were tested, namely, enrichment in living and dead microalgae, rhizofiltration and sorption through peptides from microbial cells and waste biomass (biosorption). Hemp shives and sugar beet residues showed the highest sorption rates. Recovery of the pure metals from the metal-enriched

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 3 | Overview of resources that can be recovered from different MSW streams, recovery technologies applied, recovered products, scale, TRL, region and project information

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Biodegradable fraction of MSW	Energy, nutrients	Separate collection at city level, centralised AD (digestion) and composting	Biogas, electricity and thermal heat, compost	Macro	8	Ljubljana, Slovenia	Centralised AT and composting at city level, e.g., RCERO	2007–2015	http://www.rcero-ljubljana.eu/upload/dokumenti/rcero_ljubljana_brusura_ang.pdf
		Separate collection at city level, centralised AD (digestion)	Methane for transportation, digestate (fertiliser)	Macro	8	Reykjavik, Iceland	Centralised methane recovery at city level CIRCLENERGY	2017–2018	https://www.carbonrecycling.is/circlenergy
	Nutrients, lipids, cellulose	Microbial conversion of nutrients to high-value compounds in a biorefinery approach	Ectoine, PHA, biogas, cellulose, construction materials	Meso, macro	6	Spain	DEEP PURPLE	2019–2023	https://deep-purple.eu/
	Organic carbon, energy, nutrients	Closed-vessel composting system with integrated plant biofilter	Biomass, odour removal, oxygen	Micro, meso	6	Austria, Greece, Spain	HYDROUSA, HOUSEFUL	2018–2022	https://www.alchemia-nova.net/projects/houseful/
Food waste and primary sludge	Carbohydrates	Acetogenesis (anaerobic digestion)	VFAs	Micro	3–4	Sweden	CarbonNextGen	2018–2020	https://resource-sip.se/projects/nasta-generations-koldioxidneutrala-avloppsreningsverk-carbonnextgen/
Food and garden waste + construction and demolition waste (CDW)	Green waste compost + crushed CDW material	Green waste compost and CDW are mixed 50:50	Improved soil-like substrate	Micro, meso	6	Scotland	The James Hutton Institute	2019–2021	https://www.hutton.ac.uk/staff/luke-beesley

DEEP PURPLE: Conversion of diluted mixed urban bio-wastes into sustainable materials and products in flexible purple photobiorefineries. HOUSEFUL: Innovative circular solutions and services for new business opportunities in the EU housing sector. HYDROUSA: Demonstration of water loops with innovative regenerative business models for the Mediterranean region. RCERO: Regional Waste Management Center of Ljubliana.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

biomass was achieved through hydro- and pyrometallurgical pathways. The results suggested hydrometallurgical recovery directly from the leachate to be the most feasible option.

Resource recovery from the biodegradable fraction. If biodegradable municipal waste (garden and food waste from households, restaurants, supermarkets) is separated from other MSW at the source, it can be used as a carbon and nutrient source to produce several safe (uncontaminated) and valuable bio-based products (Atasoy *et al.* 2018). With 88 million tonnes of food waste produced in the EU every year (Kibler *et al.* 2018), this represents a waste stream with great potential for resource recovery. Composting and anaerobic digestion are commonly used processes.

Besides applying green waste compost (GWC) directly to fields and green spaces, it can also be mixed with deconstruction materials (CDW) to create a functional soil-like substrate (Table 3, *The James Hutton Institute*). CDW and GWC represent the mineral and organic parts of soil, respectively. In experiments growing ryegrass *Lolium perenne* and reed canary grass *Phalaris arundinacea*, a 50:50 volumetric ratio substrate yielded significantly greater biomass than other mixing ratios, and greater than that of the control soil (local topsoil). Such ‘technical’ soils and substrates can be produced from a range of urban wastes and, after physical, biological and chemical testing and verification, are envisaged as possible replacements to degraded or sealed soils in urban environments, creating bulk soils for the restoration of old capped landfill and mine site areas, and as alternative substrates for the growth of bioenergy crops (Nehls *et al.* 2015). Monitoring of leachates from such created substrates is required as materials such as CDW can contain high quantities of problematic components like gypsum, for example, which results in sulphate leaching.

Biomethane production and further heat and electricity production are common resource recovery technologies for kitchen waste (biodegradable fraction of MSW). Co-digestion of food waste with other waste, such as municipal wastewater (sludge) has been found to achieve a substantial increase of energy generation. Estimates of methane yields from various substrates can be found in the Methane Yield Database: online infrastructure and bioresource for methane yield data and related metadata (Murovec *et al.* 2015) (the database is freely accessible on the web page http://methane.fe.uni-lj.si/). The digestate is used as crop fertiliser (or soil conditioner) for microalgae cultivation, and in other cases further processed for biofuel and bioethanol production. As mentioned in the section ‘Industrial waste and industrial wastewater’, VFA are valuable intermediate products of anaerobic digestion. VFAs gained from food waste have also been processed to substrate for the production of biofuels, such as methane, hydrogen (e.g., Saadiah *et al.* 2017) and biofuel (Wang *et al.* 2019) as well as biopolymers such as polyhydroxyalkanoates (PHAs) (Raganati *et al.* 2014; Domingos *et al.* 2017). Physical, chemical and biological pre-treatment (via enzymes) methods exist to improve the degradation of cellulose and hemicellulose solubilisation (Strazzera *et al.* 2018), sugars’ production and thus of VFAs (Braguglia *et al.* 2018). Atasoy *et al.* (2018) found that the organic fraction of MSW achieved the highest acidification and therefore highest yields after cheese whey and molasses (up to 40%).

Barriers

While composting and anaerobic digestion are well-established processes at mesoscale, the decentralised microscale for biogas production requires further research and development and is often confronted with legal barriers. Further, research to optimise anaerobic digestion is focused on improving biogas yield, while neglecting the quality of digestate (Logan & Visvanathan 2019). Logan & Visvanathan (2019) call for a shift from ‘biogas optimisation’ to ‘integrated biogas-digestate optimisation’. Such an approach would consider potential value addition from digestate, which is generally not commercially exploited. Value addition with products for high-value markets is still in its infancy, with most attempts currently limited to laboratory or pilot scale.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Gaseous effluents. NBS can remove, contain and degrade gaseous contaminants into non-toxic or less toxic substances. These processes use the natural ability of plants to metabolise nutrients. They can also be enhanced by microbial and fungal communities colonising plant roots and above-ground organs of plants (e.g., Wood *et al.* 2006; Xu *et al.* 2011). Together, they can purify indoor and outdoor air from common pollutants including PMs (particulate matter), SO_2, NO_x, N_2O, O_3, VOCs (volatile organic compounds) (Wei *et al.* 2017), while also utilising CO_2 as a building block for plant biomass and releasing O_2. In doing so, these living biofilters can be used to transform polluted air into clean air and simultaneously produce plant biomass which can be processed into a range of secondary materials.

However, while terrestrial plants provide their aesthetic value and other co-benefits, the pollutant conversion and photosynthetic efficiency of microalgae are much higher. Microalgae (photosynthetic microorganisms, here including prokaryotic cyanobacteria and eukaryotes) can convert 10–20% of average solar energy in a mid-latitude region to biomass energy, versus 0.5% for the fastest-growing terrestrial plant, switchgrass (Li *et al.* 2008). Besides their high growth rate, microalgae can tolerate high CO_2 concentrations in gas streams; e.g., *Spirulina* sp., *Scenedesmus obliquus* and *Chlorella vulgaris* grow with up to 18% CO_2 (Morais & Costa 2007), allowing for high conversion efficiencies and enabling greater biomass harvests for further processing to biofuels including biogas, bio-oil, bio-hydrogen (Li *et al.* 2008). In addition to biofuel, which is a low-value, high-volume product, a number of high-value chemicals can be derived from microalgae and are already widely marketed, such as omega fatty acids and astaxanthin (Borowitzka 2013). The commercial cultivation of microalgae has rapidly increased over the last decades (Plaza *et al.* 2009).

NBS applied for resource recovery from gaseous effluents essentially include technologies using plants, plant-surrounding microorganisms as well as microalgae photobioreactors (PBRs) to store CO_2 and produce oxygen and biomass for further uses. These technologies are designed to purify ambient air, or by injecting gas directly into systems such as algae panels or tubes, or green walls. Table 4 gives an overview of recent and ongoing research projects recovering secondary resources and products from gaseous effluent streams in cities.

Technologies and products

The origin of plant-based air treatment goes back to the 1980s, when Wolverton *et al.* developed the first systems for NASA (Wolverton & McDonald 1983; Wolverton & McDonald-McCaleb 1986; Wolverton & Wolverton 1993). Within the last years, several plant-based air treatment systems have been developed at mesoscale, like Cloud Garden in the Netherlands (Cloud Garden 2019) and Green City Solutions in Germany (Green City Solutions 2019).

Green walls and microalgae structures are the most popular applications, usually applied with the foremost objective to purify ambient air in cities, i.e., bioremediation of indoor or outdoor air, binding or degrading various air pollutants. Especially, indoor air purification can have significant human health benefits as people in industrialised countries spend approximately 22 hours per day indoors. Air pollutants, which are generated indoors, e.g., VOCs, often accumulate due to limited ventilation (Pettit *et al.* 2018). Amid global warming, technologies such as active green walls, i.e., with active aeration, will gain importance due to their co-benefits of reducing indoor temperatures by 4–6 °C if close to an indoor wall (Fernandez-Cañero *et al.* 2012).

Outdoor structures with public visibility are typically designed to enhance the aesthetic value of urban spaces, such as green walls and the microalgae structures installed by EcoLogicStudio in the UK and other European countries. Green walls have been set up at all scales, from small indoor units to outdoor multi-storey facades, e.g., by Grünwand (Techmetall 2019) and the famous ‘vertical forest’, a high-rise apartment building in Milan designed by the architect Stefano Boeri, featuring 20,000 plants, 800 trees and over 100 different species. The vertical forest absorbs 40 tonnes of CO_2 and 1.5 tonnes of fine PM each year, generating 90 tonnes of oxygen per year (Bezemer 2017).

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 4 | Overview of resources that can be recovered from different gaseous effluent streams found in cities, recovery technologies applied, recovered products, scale, TRL, region and project

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Vehicle exhaust gases, road traffic	CO_2-C, clean air	Glass tubular photobioreactors using algae	Combustible biomass, oxygen	Micro	7	Geneva, Switzerland	Culture Urbaine	2014	https://urbannext.net/culture-urbaine/
Outdoor air in urban spaces	Clean air	Plant-based green wall	Filtered air	Micro	5	EU	Green INSTRUCT	2016–2020	https://www.greeninstruct.eu/
		Large-scale green wall facade	Filtered air	Micro	8	Austria	Grünwand	2009–2013	https://gruenwand.com/
	CO_2-C, clean air	Mobile pods with tubular algae PBR structures	Oxygen, canopy area	Micro	3	Hungary	Chlorella Oxygen Pavilion	2012	Miklosi (2013)
		Curtain style vertically positioned algae reactor	Bioplastics, oxygen	Micro	6	United Kingdom	photo.Synthetica, EcoLogicStudio	Since 2018	https://www.photosynthetica.co.uk/
		Open algae tanks	Animal feed (protein), filtered air	Meso	7	Bangkok, Thailand	EnerGaia	Since 2009	https://energaia.com/
		Bio-wall type moss system	Filtered air	Micro	6	Germany	CityTree	Since 2015	https://greencitysolutions.de/en/
	CO_2-C, energy, clean air	Flat-panel photobioreactors (PBRs) using algae	Heat, biogas, oxygen	Micro	7	Hamburg, Germany	Building with Bio-Intelligent Quotient (BIQ)	2011–2013	https://www.buildup.eu/en/practices/cases/biq-house-first-algae-powered-building-world
		Wastewater treatment by open raceway algae ponds, anaerobic digestion, digestate dewatering, lipid extraction, biogas upgrading	Biofuel, biofertiliser, biomethane	Macro	6	El Torno Chiclana, Spain	All-Gas	2011–2016	http://www.all-gas.eu/en/
Industrial flue gas	CO_2-C, clean air	Vertically positioned plastic discs generating algae biofilms; continuous harvesting	Dry biomass, oxygen	Meso	5	Spain	ALGADISK	2012–2014	https://algen.eu/node/153
	CO_2-C, energy, clean air	Photobioreactor and photofermentation, anaerobic digestion of cyanobacteria residue	Bioplastic (polyhydroxybutric acid, PHB), biogas, nutrients for bacteria cultivation, fertiliser	Meso	6–7	Austria	CO_2USE	2012–2015	https://www.energy-innovation-austria.at/article/co2use-2/?lang=en
Indoor air	Clean air	Active hydroculture plant-based air treatment chambers	Filtered and humidified air	Micro	6	Denmark, UK, Switzerland, Spain	RECO$_2$ST	2018–2022	https://reco2st.eu/
Indoor air (households and other buildings), or flue gas from biogas CHP	CO_2-C, energy, clean air	Wall décor type algae biofilms; combination with biogas Combined Heat Power	Filtered air, biogas, electricity, heat	Micro	7	Germany	SOLAGA	Since 2015	https://www.solaga.de

ALGADISK: Novel algae-based solution for CO_2 capture and biomass production. Green INSTRUCT: Green INtegrated STRUCTural elements for retrofitting and new construction of buildings. ReCO2ST: Residential retrofit assessment platform and demonstrations for near zero energy and CO_2 emissions with optimum cost, health, comfort and environmental quality. SOLAGA: Living wall elements with algae.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

As listed in Table 4, NBS can be used to derive a number of products from gaseous effluents. Plant-based technologies filter the air and convert CO_2 to biomass and O_2, producing opportunities for biomass processing to various mentioned products, while also improving ambient air quality. Low-value, high-volume products are mentioned in the section 'Urban wastewater'. High-value chemicals derived from microalgae include β-carotene, astaxanthin, docosahexaenoic acid, eicosahexaenoic acid, phycobilin pigments and algal extracts for use in cosmetics as well as polyunsaturated fatty acids, widespread 'superfoods' *Chlorella* and *Spirulina* (Borowitzka 2013), bioactive medicinal products, antioxidants, colouring agents and vitamins (Khan *et al.* 2018). Aromatic essential oils can be derived from plants used for phytoremediation. Processes such as steam distillation ensure that the oils are free from unwanted contaminants including heavy metals (Pandey & Souza-Alonso 2019). The following section describes case studies at micro, meso and macro level.

Micro. *RECO$_2$ST* (Table 4) is an EU-funded building renovation project aimed to achieve major energy savings through optimised refurbishment and integrated installation tools, including NBS, specifically, two biotechnical air treatment systems for purification, cooling and humidification of indoor air. The first is a mobile pot plant-based unit either as part of a retrofit or as a standalone unit. In the second system, ambient indoor air is treated by directing ventilation through a 'wintergarden'-like plant chamber. Both systems are hydroculture, with active aeration and automated sensors measuring air quality parameters. They can reduce PMs, VOCs, achieve stable indoor temperatures, rehydrate the air and enrich building aesthetics. As a result, overall quality of life, human health and productivity of the building inhabitants will be significantly improved. Current demo sites include apartment blocks in Frederikshavn (Denmark), London (UK), Vevey (Switzerland) and Cadiz (Spain). The ideal application is in office buildings, which are densely populated for many hours a day.

Meso. The *BIQ-building* (Table 4) in Hamburg, Germany, is the first algae-powered building in the world (IBA Hamburg GmbH 2013). Microalgae are bred in the glass facades, providing sufficient biomass to cover electricity and heat requirements of the whole building. Completed in 2013, *BIQ* is a five-storey, 15-apartment passive house designed by the Austrian architectural firm Splitter-Werk and funded by the Hamburg-based Climate Concept Foundation. The building features two types of photobioreactor (PBR) facades, where algae are grown for energy production as well as for controlling light and shade. The PBRs are filled with microalgae culture medium and supplemented with CO_2. Flue gas from a biogas-fuelled micro-CHP (combined heat and power) unit is injected into the PBRs. Circulated culture medium is collected at a central location within the building where recovered heat is drawn off by a heat exchanger and collected algal biomass is shipped to an off-site biogas unit. For infrastructural and legal reasons, biogas is not generated within the building. The PBR facades of *BIQ* generate 15 g total solids (TS) per m^2 per day across 200 m^2 (300-day indicator), yielding 2,600 m^3 methane and 6,000 kWh of net energy equivalent per day.

In the *CO$_2$USE* project (Table 4), cyanobacteria convert off-gas from an industrial production plant to biomass, which is further processed to bioplastic (PHB) as well as to biogas and digestate. The digestate is used to provide nutrients for bacteria cultivation and as common agricultural fertiliser. An ecological assessment showed that greenhouse gas emissions from PHB production can be up to 75% lower than for conventional polypropylene (BMVIT 2017).

Macro. In the EU-funded *All-Gas* project (Table 4), microalgae are cultivated in high-rate algal ponds (HRAP) with raceway design (with closed loop recirculation channels), filled with pre-treated urban wastewater. CO_2-containing flue gas from the biogas upgrading column is injected into the ponds and converted to algal biomass and further to secondary bio-products. An anaerobic digester converts the harvested algal biomass to biogas and digestate. Biofuel is gained through lipid extraction from dried digestate. The residue from lipid extraction is distributed as biofertiliser. The

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

total 4 ha site located at a municipal WWTP in Chiclana, Spain, generates around 400 tonnes of biomass per year.

Barriers

Challenges to comparison and further development of active botanical biofilters are the diverse experimental approaches assessing their performance, including different structural designs, different types and doses of pollutants as well as different time frames (Pettit *et al.* 2018).

Plant-based air purification systems are limited by their metabolic detoxifying capacity, thus requiring significant area compared to common purification systems. However, vertical structures enable greater plant density for floor space. Su & Lin (2015) found that, within an hour, a 6 m^2 indoor green wall could lower CO_2 concentrations from 2,000 to 800 ppm in a 39 m^3 room. In outdoor set-ups, the reduction rate is much smaller, but the aesthetic and stress-reduction potentials of greener cities argue for plant structures at larger scales. However, the maintenance required for healthy plants and their microbial populations remains a major drawback (Pettit *et al.* 2018). For plant systems, the use of invasive species poses a threat to sustainability and long-term feasibility (Pandey & Souza-Alonso 2019).

One side effect of plants, especially in cities, is their VOC emission. In that context, use of species from the genus of *Populus*, *Salix*, *Platanus* and others might be problematic. Isoprene emission from leaves of these species in summer months can increase formation of tropospheric ozone and other secondary pollutants in air (Sharkey *et al.* 2008). Consequently, a selection of plants with low VOC emissions themselves for plant-filter use is of great importance.

Another limitation is the diffusion of gaseous pollutants and associated removal inefficiencies, which can be mitigated by active airflow through plant substrate, e.g., active green walls (Pettit *et al.* 2018) or microalgae PBRs (Malinska & Zabochnicka-Swiatek 2010). On the other hand, high contaminant concentrations can inhibit plant and algae growth, i.e., their purifying activity. While microalgae growth is not limited by NO_x, SO_x concentrations above 400 ppm can lead to the formation of sulphurous acids and lower the pH. If the pH reaches below 4, the productivity of microalgae is reduced. This can be mitigated by applying NaOH to increase the pH (Malinska & Zabochnicka-Swiatek 2010). When microalgae (or plants) are harvested and processed for biofortification or fertiliser uses, careful analyses are necessary to exclude risk of contamination (Pandey & Souza-Alonso 2019). Closed PBRs overcome problems of external contamination (Malinska & Zabochnicka-Swiatek 2010). Regarding plant biofilters, it is suggested to use non-edible high-value crops for the treatment (Pandey & Souza-Alonso 2019).

Finally, a major challenge is that many secondary commercial products that can be derived from microalgae require further R&D to become profitable (Borowitzka 2013), such as PCB bioplastics (BMVIT 2017). The design of advanced PBRs, methods to enhance microalgae growth rates, the harvesting and drying methods, product synthesis and biomass pre-treatment are cited as crucial to improve cost-effectiveness of microalgae systems (Li *et al.* 2008; Malinska & Zabochnicka-Swiatek 2010; Khan *et al.* 2018). For mass microalgae production, flat plate and raceway PBRs are economically feasible, as opposed to horizontal tubular PBRs (Malinska & Zabochnicka-Swiatek 2010). Another factor for commercialisation is the highly disparate sizes of the markets for biofuels and high-value derivates, which may change in the light of current increased efforts to commercialise and develop new microalgae products (Borowitzka 2013).

SOURCE-SEPARATED WASTE

By implementing source separation solutions, domestic waste streams can be collected with higher nutrient levels and higher concentrations of organics (COD, BOD), for which clever sewage treatment

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

and recovery technologies have been conceived. Such technologies minimise the release of toxic substances and protect natural freshwaters from eutrophication due to excess nutrient loadings (Finger *et al.* 2013). To obtain concentrated waste streams, dilution of solid and aqueous wastewater needs to be prevented. First of all, a separate sewer system with a sanitary and storm sewer can increase pollutant concentrations in wastewaters by around 85%, as calculated from typical German flow rates (Brombach *et al.* 2005).

Second, several options have been proposed for source separation at the household level of either urine (yellow water (YW)), using water-free urinals or source separation (NoMix) toilets and brown water (feces), or black water (BW). The latter waste stream combines urine and feces but in the selected case studies, dilution is avoided by means of vacuum toilets requiring low amounts of flushing water, and further separated vacuum transport. Another option is waterless dry toilets with or without urine separation. The collected dry toilet matter (DTM), depending on the type of toilet, can contain feces, urine, toilet paper and structural material. The sanitary wastewater from the laundry, kitchen, shower and bath is referred to as greywater (GW) and is separately collected as well. Finally, organic waste produced in cities can also be separated. We note the difference between kitchen waste (KW); bio-waste (Bio-W) referring to the combination of food waste and more general, the biodegradable fraction of catering waste; vegetable, fruit and yard waste (VFY), which is collected separately in several European cities; and green waste (GrW) collected in gardens and urban green spaces.

Coupling source separation to decentralised treatment/recovery of domestic wastewater, dry toilet matter and household waste (fractions) allows the recovery of valuable resources such as nutrients, organics, energy and water more efficiently. Table 5 gives an overview of recent and ongoing research projects recovering secondary resources and products from different source-separated waste and wastewater streams in cities.

Technologies and products

Micro. *Sanitation 360* aims to produce fertiliser from human urine inside the toilet. The natural and fast enzymatic degradation of urea is chemically inhibited at pH 10 (Randall *et al.* 2016; Senecal & Vinnerås 2017; Simha *et al.* 2018). Thereafter, the water in the YW is evaporated and ventilated away leaving a fertiliser product with commercial-grade nutrient concentrations (>10% N, >1% P and >3% K). The decentralised inside-the-toilet approach to urine management allows large-scale implementation without major changes in the infrastructure, only requiring a new toilet and a drying bed. The first pilot systems have been implemented in single urine-diverting toilets in Sweden. A similar system has been implemented in the Autarky toilet developed at the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) in Switzerland, where the YW is treated and used locally for fertiliser production (Larsen *et al.* 2015).

At the *Forum Chriesbach* office building in Duebendorf, Switzerland, a YW nutrient recovery system for 220 people has been in operation since 2012 (EAWAG 2019). YW is collected with waterless urinals and NoMix toilets and is directed to collection tanks in the basement. The urine is then nitrified in an aerated bioreactor (Etter *et al.* 2013), followed by a polishing step with activated carbon to eliminate pharmaceuticals and hormones. A vacuum distillation step reduces the liquid volume by 93% and eliminates pathogens. The product, a concentrated and processed urine-based fertiliser, contains all primary and secondary nutrients of the collected urine and is a fully approved fertiliser in Switzerland. It is produced and marketed as 'Aurin' by Vuna GmbH, a spin-off company of EAWAG (VUNA GmbH 2019). The main success factor was the determination of the EAWAG board to realise the new office building as a lighthouse project for integrated sustainable building practices, as well as the approval and support of the Swiss national authorities. The water and sanitation system was an important part of this broader context.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Table 5 | Overview of technologies applied to recover resources from source-separated urban waste(water), different secondary resource streams, recoverable resources, technologies applied, recovered products, scale, TRL, region and project

Secondary resource stream	Recoverable resource	Technologies applied	Products	Scale	TRL	Region	Project	Project period	Reference
Source-separated urban WW + kitchen waste	Reclaimed water, energy and nutrients	Vacuum collection, AD, OLAND, struvite precipitation, AD, heat exchange, district heating	Biogas, struvite fertiliser, thermal energy (heat)	Meso	8	Sneek, The Netherlands	Lemmerweg and Noorderhoek RUN4LIFE	2017–2021	http://run4life-project.eu/
		Vacuum toilets and collection, AD, struvite precipitation, AD in a membrane bioreactor, RO, heat exchange, district heating	Biogas, struvite fertiliser, heat, water reuse for industry	Meso	8	Ghent, Belgium	De Nieuwe Dokken RUN4LIFE	2017–2021	http://run4life-project.eu/
		Water-free urinals, vacuum toilets, AD, struvite precipitation	Biogas, struvite fertiliser, thermal energy (heat)	Meso	7–8	The Hague, The Netherlands	Rijkskantoor, Rijnstraat, NL	2017	https://www.saniwijzer.nl/projecten/rijkskantoor-rijnstraat-8/detail=94
Yellow water	Nutrients	Inside-the-toilet urine drying after chemical stabilisation	Dry fertiliser	Micro	7	Sweden	Urine dehydration technology for sanitation 2.0. Sanitation 360	2015–2018	https://www.slu.se/en/departments/energy-technology/projects/kretslopp/productive-on-site-sanitation-system/
		Water-free urinals, NoMix toilets, nitrification, activated carbon, distillation	Concentrated liquid fertiliser 'Aurin' (VUNA GmbH)	Micro	8	Duebendorf, Switzerland	VUNA – Nutrient Recovery from Urine	2010–2015	https://www.eawag.ch/en/department/eng/projects/vuna/
Grey water + dry toilet matter	Nutrients, organic carbon	Constructed wetland for greywater treatment; waterless dry toilets, composting and vermicomposting	Compost	Meso	8	Cressy, Geneva, Switzerland	Cooperative Equilibre @ Cressy	2011–2018	https://www.cooperative-equilibre.ch/projects/cressy/historique-de-limmeuble-de-cressy/
Grey water	Reclaimed water and nutrients	Green walls, vertical facade farming, vegetarian roof restaurants, aquaponics	Fertigation water	Meso, macro	7	Northern and central EU	EdiCitNet	2018–2023	https://cordis.europa.eu/project/rcn/216082/factsheet/en
Blackwater	Nutrients	Separate BW collection, centralised treatment with either ammonia sanitisation or AD with urea addition	Concentrated liquid fertiliser	Meso	7	Uddevalla[a], Västervik[b], Strängnäs[c], Örebro[d], Västerås[e] Sweden	Centralised BW treatment for >10 households	Implementation since [a,b]2013, [c]2014, [d]2015, [e]2018	https://pdfs.semanticscholar.org/f5dd/

EdiCitNet: Edible Cities Network Integrating Edible City Solutions for social resilient and sustainably productive cities. HOUSEFUL: Innovative circular solutions and services for new business opportunities in the EU housing sector.

[a,b,c,d,e]Dates refer to implementation of projects listed in the Region column.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Meso. The city of Sneek in the Netherlands has two areas with source separation systems: *Lemmerweg* (since 2005) and *Noorderhoek* (since 2010). BW is collected by means of vacuum collection (toilets) and transport systems that require about seven times less water (1 L per flush) than conventional sanitation. The developed sanitation concept (Zeeman *et al.* 2008) was first tested for several years with 32 houses at *Lemmerweg*, and subsequently applied for 232 households in *Noorderhoek*. The highly concentrated BW is mixed with ground KW and treated anaerobically in an upflow anaerobic sludge bed (UASB) reactor (Lettinga *et al.* 1981). A similar concept is now under construction for 550 houses in Amsterdam. The influent COD load is degraded, on average, for 70% resulting in a yearly biogas production of 10.5 Nm^3/IE/a (Wit *et al.* 2018). Biogas energy is recovered as heat and used in a district heating system. Nitrogen is removed from the UASB effluent, using oxygen-limited autotrophic nitrification/denitrification (OLAND) (Vlaeminck *et al.* 2009). Phosphate is recovered as struvite and locally reused as fertiliser. GW is, together with the BW effluent, aerobically treated. GW has the highest temperature and energy potential to recover, and heat recovery through heat exchangers allows the transfer of most of the energy to the district heating system. A schematic representation of the applied concept is given in Figure 3.

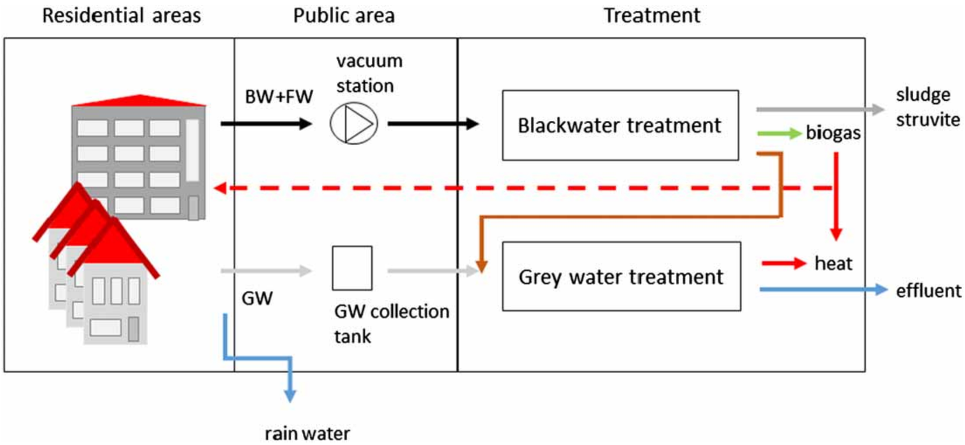

Figure 3 | Schematic representation of the projects in Sneek, The Netherlands (redrawn and adapted from Wit *et al.* 2018).

Similar examples are being set up throughout Europe. For example, the urban renewal project 'H + ' in Helsingborg, Sweden consists of an old port and industrial areas, in which 320 apartments plus offices for 2,000 workers will have source separation systems. In order to reach its future sustainability goals, the city of Helsingborg has established cooperation between the municipal waste, energy and water companies. This Swedish eco-district is part of the *Run4Life* project, together with *De Nieuwe Dokken* district in Ghent, Belgium, and a new pilot at the previously mentioned *Lemmerweg*, and a pilot site in the industrial park of Porto do Molle (Vigo, Spain).

In the *De Nieuwe Dokken* project, the same decentralised treatment scheme will be applied as in the *Noorderhoek* project, similarly as depicted in Figure 3. The multi-step treatment concept is currently being set up for 400 households (1,265 IE), which will allow recovery of 1,600 kg/a struvite, to be used as slow-release fertiliser in the local green areas and urban farming projects, and up to 800 MWh_{th}/a through biogas utilisation and mostly GW excess heat recovery through heat exchangers (part of the NEREUS project, funded by the EU Interreg 2Seas program 2014–2020). In total, about one-third of the total heat demand of the urban area (2.1 GWh/a) can be provided by the decentralised treatment plant (Buysschaert *et al.* 2018). In contrast to the *Noorderhoek* projects, water reuse will be included after treatment of the GW in a membrane bioreactor (MBR), a cation exchange unit and reverse osmosis (RO) to remove pathogens, nutrients and hardness. In total, more than 30,000 m^3/a water will be reused as process water in a nearby factory. Furthermore, the excess

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

heat of the factory will be recovered by coupling it to the district heating system, thus meeting the remaining two-thirds of the total heat demand. As such, this demonstration project couples recovery of energy and water, and the industrial activity and urban metabolism within a city.

Another example of source separation and recovery of resources at meso level is in the *Rijksgebouw* in The Hague, The Netherlands, which houses the Ministries of Foreign Affairs, Infrastructure and Water Management. The main incentive of the project at the Rijnlaan is to reduce water use and to recover nutrients and energy (Stichting 2017). In the basement of the building, source-separated YW and BW of ±6,000 office workers are treated. A part of the YW is collected in water-free urinals (approximately 200 L/day) and more than 95% of the phosphate is recovered as struvite. The struvite is applied in the facility as fertiliser in the enclosed garden of the office building. BW collected in vacuum toilets (3 m^3/day), and in the future combined with food waste (500 kg/day), is digested to produce biogas. The biogas is used in a central heating boiler, which is providing the energy for a hot water buffer tank to heat the building.

In the *Jenfelder Au* in Hamburg, Germany, the so-called *Hamburg Water Cycle®* is installed in a new neighbourhood for approximately 830 residential units. As in the other above-mentioned projects in Sneek, The Hague, Ghent and Helsingborg, BW (approximately 12 m^3/day) is collected via vacuum toilets and transported via a vacuum sewer to an anaerobic treatment system. In contrast with the other projects mentioned above in the Jenfelder Au, a mesophilic completely stirred tank reactor (CSTR) is implemented instead of a UASB reactor. Gas production in the Jenfelder Au is increased by adding external substrate from grease separators (maximum 30 m^3/day with approximately 6% dry matter). The digestate of the CSTR is expected to be used in agriculture after a post-treatment step (to be determined). Greywater will be treated via a fixed bed reactor in a first step. Further treatment processes will be examined in a test unit in order to determine the most effective one for different reuse purposes. The vacuum system has been in operation since 2017. The CSTR was opened in June 2019. The construction of the fixed bed reactor started at the end of 2019.

In Cressy (Geneva, Switzerland) the cooperative society 'Cooperative Equilibre' (CE) realised a three-storey/13-apartment building in 2011, which completely separates toilet waste from the water cycle. The toilet waste is collected with non-separating dry toilets, together with wood-chippings as structural material. The greywater is treated on-site in a constructed wetland. The DTM of each apartment is vermicomposted in the basement in a separate 1 m^3 container. Every 6–12 months, approximately 100 litres of pre-composted DTM are manually conveyed to a second composting step in the garden. After completion of the composting process (two years), the compost is used for fertilising trees and shrubs in the garden. Since 2011, CE has realised two more projects with a total of 103 apartments in Geneva following the idea of decentralised sanitation (including dry toilets) in an urban setting.

In areas with sensitive water recipients in Sweden, it is not allowed to apply (treated) BW as such into the environment. Lately, BW has been stored and sanitised in a large tank on a farm prior to reuse as fertiliser. The systems either sanitise the feces with ammonia sanitisation (addition of urea followed by >3 months storage) (Nordin *et al.* 2018), or a combination of biological (autothermal thermophilic aerobic digestion, ATAD) treatment followed by urea addition. ATAD increases the temperature allowing for less urea addition and shorter treatment time (Nordin & Vinnerås 2015). These centralised BW treatment systems have been set up in several municipalities in Sweden. Uddevalla has the largest number of connections with an annual treatment capacity of approximately 3,000 m^3, corresponding to 200–300 households. In total, over 1,000 households are covered with this type of system in over ten Swedish municipalities. In this way, nutrients are recycled for agriculture, with less transport of fertilisers and water.

Macro. Source-separated GrW is collected separately in many European countries and converted to energy and compost in large-scale centralised AT and composting facilities. In general, the waste

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

treatment facilities apply thermophilic (dry) digestion and the digestate requires post-composting to stabilise. The compost is sold through commercial channels. This technology is used all over Europe to recover biogas/methane from separately collected organic waste and the mechanically separated fraction of organic waste from mixed waste. For example, *RCERO* in Ljubljana, Slovenia, is processing waste for around one-third of Slovenia (700,000 people), which amounts to around 150,000 tonnes of mixed municipal waste and 20,000 tonnes of separately collected food waste (Guardian 2019). The combined organic waste is treated in two-stage (thermophilic-mesophilic) plug-flow anaerobic reactors. Biogas is converted via a CHP to electricity and heat, which are both used on-site. The digestate (35,000 t/a) is dehydrated and further processed to produce 7,000 t/a compost.

Centralised methane recovery (Table 5) allows the use of the methane in biogas produced from bio-W, VFY and/or GrW at city level, in order to power, e.g., local transport. The city of Reykjavik, Iceland and its surrounding municipalities, home to about 150,000 inhabitants, collects all organic waste (60% biomass, 40% food waste) in a landfill (a bioreactor is being constructed). The biogas from the landfill has an exceptionally good quality with over 95% methane, which can be used directly in combustion engines. A pipeline from the landfill delivers the methane to gas stations for cars and trucks. About 2% of the personal cars run on methane, all of the city garbage trucks and some company trucks. In 2018, the construction of a modern biogas reactor was started, and it is estimated that methane production will triple, providing biofuel for up to 10% of the cars. A switch of the city buses from diesel to methane is under discussion. These actions are part of an ambitious climate action plan from the Icelandic government. The current government aims to ban registration of new gasoline and diesel buses by 2035 to become carbon neutral by 2040.

Barriers

Barriers for implementation of the above-mentioned concepts are related to the economy (of scale) and safety of operation. For example, the lack of sufficiently safe handling practices in the case of nutrient recovery from faeces or DTM poses a barrier. The removal of organic micropollutants and other contaminants such as microplastics, and hygienic safety of the recovered products are important as well. Recovery of COD and P is easier, since technologies are commercially available, but the recovery of N (and K) as a separate product is a problem. Only for streams with a very high N concentration, like urine (YW), are N-recovery technologies available, but during storage of urine a significant part of the nitrogen (about 50%) is potentially lost to the atmosphere due to premature hydrolysis to ammonia in, e.g., piping. Stripping of ammonia is technologically feasible but is currently not implemented because of the high energy and chemical demand. Another proven technique for N (and other nutrients) recovery from urine is nitrification (Udert & Wächter 2012), followed by a polishing step with activated carbon and vacuum distillation as applied for the urine collected in the EAWAG building. Another barrier for urine collection is the market availability of NoMix toilets. Several models have been removed from the market due to problems during use. Only dry toilets and water-free urinals are proven technologies. Recently, the new NoMix toilet 'Safe' was introduced and will probably be marketed at the beginning of 2020. A series of pilot projects in Switzerland and abroad are expected (EAWAG 2019).

When considering the reuse of products from domestic wastewater, for example as fertiliser in (urban) agriculture, the product quality is essential for environmental protection, as well as hygienic safety and user acceptance. In the case of dry toilets, the reuse of compost produced from DTM faces regulatory barriers if the compost is used beyond the owned plot of land. Another example of quality issues is contamination with microplastics since the implemented technologies for reuse of digestate and compost from municipal bio-waste do not completely remove microplastics (Weithmann *et al.* 2018). For example, Slovenia allows up to 0.5% (dry weight) of plastics that is larger than 2 mm in

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

compost and up to 2% (dry weight) of plastics in digestate. Technologies for achieving high-quality products, like membrane filtration, heating, AOP, activated carbon are available but will increase costs. The balance between risks and costs is to be established. In many European countries, the legal framework is currently limiting the possibilities of reusing products from wastewater in agriculture.

Scale is another factor of importance. The concept applied in Sneek, Ghent and Helsingborg is not suited for single or a few houses. Wit *et al.* (2018) calculate that this system becomes competitive with conventional sanitation (references: 30,000 and 100,000 inhabitants) at a scale of around 3,000 inhabitants (price of nutrient products is set at zero). In contrast, the concept applied in Cressy is limited to a maximum of three storeys, due to space constraints. Furthermore, the existing sanitation infrastructure represents an additional barrier since source separation sanitation requires new infrastructure. Most industrialised countries, however, are characterised by a high-density sewer network (with a very long lifetime) connected to municipal wastewater treatment plants; sewer and wastewater treatment plants have different lifetimes. According to Zeeman (2012), a gradual replacement is the only affordable way to introduce 'New Sanitation' at a larger scale, and the development of a transition strategy is required. Close cooperation between involved stakeholders, like that established in Sneek, Ghent and Helsingborg is crucial.

Another important aspect to convince the stakeholders and to remove the roadblocks for implementing new eco-technologies in an urban settlement is the integration of the local community and a sound business model, based on the development of new waste-based and circular value chains. Therefore, energy service companies (ESCO) can be set up to organise the technical maintenance and district services. For example, in the *De Nieuwe Dokken* project in Ghent, Belgium, the ESCO is a mixed private–public–citizen initiative in which the local inhabitants are represented, together with investors and public stakeholders such as the local water utility, FARYS. The local community will benefit directly from the revenues of the recovered products and the local district heating system. In the two projects at Sneek, The Netherlands, the conventional division of tasks was chosen in a cooperation between the housing cooperation – responsible for the indoor infrastructure (toilet and piping), the municipality – responsible for the outdoor infrastructure (vacuum station and sewer) and the water board – responsible for the treatment/recovery technologies. As in Ghent, the inhabitants pay the usual taxes and nothing more. A residents' satisfaction survey was done twice in the project in Sneek. Residents are predominantly satisfied with the system and consider it handy and hygienic, although some people had to get used to the vacuum toilet and kitchen grinder. The provided demonstration and the available information were highly appreciated (Wit *et al.* 2018).

DISCUSSION AND CONCLUSION

Resource recovery systems for urban residue streams comprise collection, transport, treatment/recovery and reuse. It is crucial to consider each step as, e.g., collection and transport will have an effect on applicable technologies for recovery and moreover on quality of products for reuse. When more dilution is allowed during collection and transport, the recovery technology becomes less (energy) efficient and more complex.

Common barriers

Considering barriers mentioned in the sections 'Urban wastewater', 'Industrial waste and industrial wastewater', 'Municipal solid waste' and 'Gaseous effluents', the realisation of the manifold potentials of NBS for circular cities faces a number of challenges. They can be divided into barriers related to

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

lack of awareness, current legislation, regulations and the organisation of urban infrastructures as well as technical barriers, raising the need for both further technical and social innovation.

Lack of awareness for proven capabilities of NBS

Even though they sometimes perform better than conventional grey technologies (e.g., see the section 'Urban wastewater'), NBS are de-prioritised. Despite many years of strong scientific track record, the capabilities of plants and microbes to convert nutrients into biomass, clean water and air, extraction of metals and other materials are not yet well known. Especially resource recovery projects using NBS in the narrow sense, i.e., as the European Commission understands them, plant-based systems delivering ecosystem services, are rare. Many NBS projects work to communicate their successes to policymakers and urban planners. Particularly large innovation and demonstration projects have the power to build trust and political willingness for broader implementation of NBS, and to overcome the lack of trust in NBS, even in industry. Capital expenditures for NBS are roughly on a par with conventional grey systems (depending on the type of systems compared), but NBS incur lower operational costs and offer additional benefits. Therefore, not only economic, but also environmental and social criteria can incentivise a shift from well-known grey technologies to NBS.

Legislative, regulatory and organisational barriers

The main barriers are related to uncertainties of new system financing (new business models, etc.) and the legislation in place (Houston (CSR Europe) *et al.* 2018). Further, once a resource becomes waste, a resource recovery effort often has to go through waste legislation, thus apply and fulfil all criteria for waste management. Even if applied in small scale, the efforts for application and documentation are similar to the requirements to run large recycling facilities. Also, current legislation does not always allow the direct reuse of secondary products. For example, the Netherlands currently faces ongoing discussions on how to deal with compost produced in the city. As local household compost is usually not tested and consequentially not approved, it cannot be easily applied across the city. Standards and legal frameworks need to adapt to scientific progress, but even research itself (not only implementation) is often already challenged by regulations, when there is no exemption clause in place for research purposes. A certain flexibility of administration processes and obligations could significantly stimulate wider implementation of NBS.

While the recovery of high-value products requires investments available only at macro- (and in some cases meso-) scale, micro- and mesoscale NBS bear the greatest potential for efficient nutrient and clean water recovery through direct reuse. As mentioned above, separate nutrient recovery with NBS is not feasible, but after pre-treatment, direct reuse of NBS-recovered secondary fertigation water and fertiliser/soil conditioner for urban agriculture can keep nutrients (and water) in highly efficient short cycles. This requires new management models in cooperation among municipalities and communities (neighbourhoods), innovation of the division of responsibilities among households/residents/local communities and municipalities (bottom up) coupled with spatial planning and simplification of applicable administrative hurdles (top down). The opportunities of resource recovery for value creation can be leveraged to incentivise decentralised ownership and maintenance.

Large advances have been achieved in reducing the area requirements of NBS, most notably constructed wetlands. Yet, availability of space in cities is still an often-cited barrier for functions such as CO_2 capture and wastewater treatment. There is need for more demo case studies and comparable evaluations that can provide standardised data on the ratio of surface area to functional efficiency for different technologies, climate and other conditions to support the planning process. Meanwhile, current planning and design models and tools used for centralised infrastructure approaches are not suitable for decentralised approaches and the integration of NBS into city-scapes. This calls for research

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

to identify the optimal scale, management scheme and logistics for existing specific conditions. Spatial planning innovations could facilitate the introduction of NBS to unutilised and underutilised infrastructures (rooftops, facades, indoor spaces). This could, in turn, allow for plant structures at larger scales, thus maximising the aesthetic and stress-reduction potentials of greener cities.

Further, the wide range of secondary end-products can lead to competition among different options. Therefore, there is a need for increased assessments of supply and demand factors, setting optimal configurations of NBS and blended green-blue-grey infrastructure and making the right choice of end-products.

Remaining technical barriers

Recovery of products other than energy is gaining momentum and there is a call for process optimisation towards product purity versus energy yield optimisation (e.g., 'integrated biogas-digestate optimisation' (Logan & Visvanathan 2019)). Many technologies that enable recovery of value-added products are still in development and applied so far only at laboratory and pilot scales. The next step for these technologies will be scale-up to demo and flagship scales, to prove the hygienic safety of waste(water)-derived products and to further diversify profitable high-value secondary products. Already at this stage, the communication with public and private stakeholders is essential to prepare the market including legislative and regulatory framework for the new bio-products. While NBS can provide essential functions for resource recovery, with significant additional benefits, further processing is usually required to achieve product purity required for commercialisation. Further, the toxicity of some raw industrial or municipal waste streams limits or even prohibits plant and microbial growth. In the field of source separation and decentralised applications, further research is needed to tackle the challenges mainly related to lack of economy (of scale) and safety of operation.

End-of-life management versus circularity by design

All these solutions look into recovery of secondary resources once they become waste. In this sense, they try to solve problems only at the end of the life cycle and have to take into account that many or most of the actual urban resource stream systems are not designed to be recovered. If you design a system from scratch with circular design in mind, the resource recovery would also be designed to happen with as little energy input as possible. The process can then even be designed to keep the resource value at the highest possible level (Bocken *et al.* 2016). By mixing resources with others, one has to apply more energy to again recover the value of one resource. In this sense, separation at or close to the source can be favourable for resource recovery purposes, although we should take into consideration the additional infrastructure needs and their associated grey energy (Larsen 2011). Direct metabolisation of organic nutrients from waste streams in agricultural systems can be one of the most favourable options (Capodaglio 2017).

The use of stored solar energy in organic resources for decentralised energy generation can also be a good approach, especially in combination with recovery processes. Since CO_2 is usually the last step in biomass energy systems, such a system can at best be climate-neutral. For more sustainable process designs, one additional aim can be the direct reuse of nutrients by building up biomass and simultaneously converting again CO_2 into biomass, as it is the building block of plants and many other phototrophic organisms. For reasonable carbon capture this biomass should then be either used in long-term storage systems like buildings, for furniture, etc., or should steadily be composted and integrated as increased soil carbon content. To take resource recovery with NBS to the next level, biorefinery approaches, also at a decentralised level, can be included. In this setting we have to look more into the feedstock quantity and quality of the different resource streams and the conversion to products. In the best case, the decentralised smaller biorefineries at the city level can pre-treat a

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

certain organic residue stream and the conversion to bulk products can happen at a more centralised level (alchemia-nova 2019a). Appropriate logistics and a combination of zero km conversion of nutrients into food and exchange with the surrounding areas can be a good approach for cities. Cities can become 'major circular bioeconomy hubs' (European Commission 2018a).

The way forward

In this review paper, we identified projects, technologies and barriers for application of nature-based solutions for resource recovery in the framework of circular economy in cities. Our recommendations for further efforts are as follows:

- Replication of existing nature-based technologies for resource recovery in more cities and regional proof of concept for enabling further uptake.
- Upscaling existing and proven NBS resource recovery systems to bigger areas and for bigger settlements/regions/quarters.
- Raise the interest of investment schemes to fund more NBS cases.
- Demonstrate and stress the multifunctionality of NBS in new environments (e.g., industrial effluents or processes).
- Cooperate systematically with more actors along value chains and raise awareness.
- Share the know-how of NBS openly in developing or underprivileged countries.
- Using a value approach model as suitable means for a circular economy evaluation (e.g., value hill as tool (Achterberg & Fischer 2019)) together with other circular indicators (European Commission – Eurostat 2019).
- Comparison of direct reuse (metabolisation) of nutrients in agricultural systems vs technical recovery and shipping of nutrients back to the fields far away from the source.
- Comparing full cost accounting methods to direct nutrient conversion to agricultural produce with conventional farming systems.
- Awareness-raising for necessity of nutrient reuse from human systems and the hygienic quality of NBS.

ACKNOWLEDGEMENT

The collection of case studies happened primarily in the framework of the COST Action CA13177 Circular City ('Implementing nature based solutions for creating a resourceful circular city', http://www.circular-city.eu, duration 22 Oct 2018–21 Oct 2022) and is also deeply associated with the following projects: HYDROUSA (H2020-CIRC-2-2017, grant agreement no. 776643), HOUSEFUL (H2020-CIRC-1-2017, grant agreement no. 776708), ReCO2ST (H2020-EeB-05-2017, grant agreement no. 768576), Run4Life (H2020-CIRC-2-2016, grant agreement no. 730285).

REFERENCES

Achterberg, E. & Fischer, A. 2019 *3 Essential Steps to Financing Circular Business Models*. Check out These 3 Essential Steps to Learn How to Financing Your Own Circular Business Model! 2019. Circle Economy. Available from: http://www.circle-economy.com/financing-circular-business.

alchemia-nova 2019a *Austrian BioCycles*. Available from: https://www.alchemia-nova.net/projects/austrian-biocycles/.

alchemia-nova 2019b *Project GRecoMet*. Available from: https://www.alchemia-nova.net/projects/grecomet/.

Atasoy, M., Owusu-Agyeman, I., Plaza, E. & Cetecioglu, Z. 2018 Bio-based volatile fatty acid production and recovery from waste streams: current status and future challenges. *Bioresource Technology* **268**, 773–786. https://doi.org/10.1016/j.biortech.2018.07.042.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Balabanič, D., Filipič, M., Krivograd Klemenčič, A. & Žegura, B. 2017 Raw and biologically treated paper mill wastewater effluents and the recipient surface waters: cytotoxic and genotoxic activity and the presence of endocrine disrupting compounds. *The Science of the Total Environment* **574**, 78–89. https://doi.org/10.1016/j.scitotenv.2016.09.030.

Bani, A., Echevarria, G., Zhang, X., Benizri, E., Laubie, B., Morel, J. L. & Simonnot, M.-O. 2015 The effect of plant density in nickel-phytomining field experiments with *Alyssum murale* in Albania. *Australian Journal of Botany* **63**, 72–77. https://doi.org/10.1071/BT14285.

Bani, A., Echevarria, G., Pavlova, D., Shallari, S., Morel, J. L. & Sulce, S. 2018 Element case studies: nickel. In: *Agromining: Farming for Metals. Mineral Resource Reviews* (Van der Ent, A., Echevarria, G., Baker, A. & Morel, J., eds). Springer, Cham, Switzerland, pp. 221–232.

Bengtsson, S., Werker, A., Visser, C. & Korving, L. 2017 *PHARIO: Stepping Stone to A Sustainable Value Chain for PHA Bioplastic Using Municipal Activated Sludge*. Available from: http://edepot.wur.nl/413277.

Bertino, G., Menconi, F., Zraunig, A., Terzidis, E. & Kisser, J. 2018 *Innovative Circular Solutions and Services for New Buildings and Refurbishments*. WIT Press, Southampton, UK, pp. 83–91. https://doi.org/10.2495/ARC180081

Bezemer, M. 2017 Phytoremediation: How Plants Help Restore Balance to Our Environment. *Into Green* (blog). December 7, 2017. Available from: https://intogreen.eu/phytoremediation-how-plants-help-restore-balance-to-our-environment/.

BMVIT 2017 CO2USE. *Energy-Innovation-Austria* (blog). 2017. Available from: https://www.energy-innovation-austria.at/article/co2use-2/?lang=en.

Bocken, N. M. P., de Pauw, I., Bakker, C. & van der Grinten, B. 2016 Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* **33** (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Mareckova, K., Pipatti, R. & Zhang, T. 2007 Waste management. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. & Meyer, L. A., eds). Cambridge University Press, New York, USA, pp. 585–618.

Borowitzka, M. A. 2013 High-value products from microalgae – their development and commercialisation. *Journal of Applied Phycology* **25** (3), 743–756. https://doi.org/10.1007/s10811-013-9983-9.

Braguglia, C. M., Gallipoli, A., Gianico, A. & Pagliaccia, P. 2018 Anaerobic bioconversion of food waste into energy: a critical review. *Bioresource Technology, Bioconversion of Food Wastes* **248**, 37–56. https://doi.org/10.1016/j.biortech.2017.06.145.

Brombach, H., Weiss, G. & Fuchs, S. 2005 A new database on urban runoff pollution: comparison of separate and combined sewer systems. *Water Science and Technology* **51** (2), 119–128.

Buysschaert, B., Vermijs, L., Naka, A., Boon, N. & De Gusseme, B. 2018 Online flow cytometric monitoring of microbial water quality in a full-scale water treatment plant. *Npj Clean Water* **1** (1), 16. https://doi.org/10.1038/s41545-018-0017-7.

Capodaglio, A. G. 2017 Integrated, decentralized wastewater management for resource recovery in rural and peri-urban areas. *Resources* **6** (2), 22. https://doi.org/10.3390/resources6020022.

Cetecioglu, Z., Dolfing, J., Taylor, J., Purdy, K. J. & Eyice, O. 2019 COD/sulfate ratio does not affect the methane yield and microbial diversity in anaerobic digesters. *Water Research* **155**, 444–454. https://doi.org/10.1016/j.watres.2019.02.038.

Chaney, R. L., Angle, J. S., Broadhurst, C. L., Peters, C. A., Tappero, R. V. & Sparks, D. L. 2007 Improved understanding of hyperaccumulation yields commercial phytoextraction and phytomining technologies. *Journal of Environmental Quality* **36** (5), 1429–1443. https://doi.org/10.2134/jeq2006.0514.

Chemiereport.at 2017 Metall Aus Müll-Asche. *Österreichs Magazin Für Wirtschaft, Technik Und Forschung* **2017**. Available from: https://www.chemiereport.at/epaper/201705/epaper/ausgabe.pdf.

Chen, X., Zhou, H., Zuo, K., Zhou, Y., Wang, Q., Sun, D., Gao, Y., Liang, P., Zhang, X. & Ren, Z. J. 2017 Self-sustaining advanced wastewater purification and simultaneous in situ nutrient recovery in a novel bioelectrochemical system. *Chemical Engineering Journal* **330**, 692–697. https://doi.org/10.1016/j.cej.2017.07.130.

Chipasa, K. B. & Mędrzycka, K. 2006 Behavior of lipids in biological wastewater treatment processes. *Journal of Industrial Microbiology and Biotechnology* **33** (8), 635–645. https://doi.org/10.1007/s10295-006-0099-y.

Cloud Garden 2019 *Cloud Garden*. Available from: https://www.cloudgarden.nl/en/.

Cordoba, P. & Staicu, L. C. 2018 Flue gas desulfurization effluents: an unexploited selenium resource. *Fuel* **223**, 268–276.

Dessì, P., Porca, E., Lakaniemi, A.-M., Collins, G. & Lens, P. N. L. 2018 Temperature control as key factor for optimal biohydrogen production from thermomechanical pulping wastewater. *Biochemical Engineering Journal* **137**, 214–221. https://doi.org/10.1016/j.bej.2018.05.027.

Diaz-Elsayed, N., Rezaei, N., Guo, T., Mohebbi, S. & Zhang, Q. 2019 Wastewater-based resource recovery technologies across scale: a review. *Resources, Conservation and Recycling* **145**, 94–112.

Domingos, J. M. B., Martinez, G. A., Scoma, A., Fraraccio, S., Kerckhof, F.-M., Boon, N., Reis, M. A. M., Fava, F. & Bertin, L. 2017 Effect of operational parameters in the continuous anaerobic fermentation of cheese whey on titers, yields, productivities, and microbial community structures. *ACS Sustainable Chemistry & Engineering* **5** (2), 1400–1407. https://doi.org/10.1021/acssuschemeng.6b01901.

EAWAG 2019 Forum Chriesbach. EAWAG. 2019. Available from: https://www.eawag.ch/en/aboutus/sustainability/sustainable-building/forum-chriesbach/.

Ellen MacArthur Foundation 2017 *Urban Biocycles*. Available from: https://www.ellenmacarthurfoundation.org/publications/urban-biocycles.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

EPEM S.A. – Environmental Planning, Engineering & Management 2011 *Database of Waste Management Technologies*. Available from: http://www.epem.gr/waste-c-control/database/html/MBT-07.htm.

Eregowda, T., Matanhike, L., Rene, E. R. & Lens, P. N. L. 2018 Performance of a biotrickling filter for the anaerobic utilization of gas-phase methanol coupled to thiosulphate reduction and resource recovery through volatile fatty acids production. *Bioresource Technology* **263**, 591–600. https://doi.org/10.1016/j.biortech.2018.04.095.

Etter, B., Udert, K. M. & Hug, A. 2013 Total nutrient recovery from urine – operation of a pilot-scale nitrification reactor. In: *WEF/IWA International Conference on Nutrient Removal and Recovery*, Vancouver, Canada. Available from: https://www.researchgate.net/publication/265966790_Total_Nutrient_Recovery_from_Urine_-_Operation_of_a_Pilot-Scale_Nitrification_Reactor.

EUBIA 2019 *Bioethanol – European Biomass Industry Association*. Available from: http://www.eubia.org/cms/wiki-biomass/biofuels/bioethanol/.

European Commission 1991 *Official Journal of the European Communities*, **34**(May). Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:1991:135:TOC.

European Commission 2018a *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*. Publications Office of the European Union, Luxembourg.

European Commission 2018b Water Reuse. *Environment* (blog). May 28, 2018. Available from: http://ec.europa.eu/environment/water/reuse.htm.

European Commission 2019 Municipal Waste Statistics. *Eurostat Statistics Explained* (blog). January 23, 2019. Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics.

European Commission – Eurostat 2019 Monitoring Framework. Available from: https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework.

Fermoso, F. G., van Hullebusch, E., Collins, G., Roussel, J., Mucha, A. P. & Esposito, G. (eds) 2019 *Trace Elements in Anaerobic Biotechnologies*. IWA Publishing, London, UK. https://doi.org/10.2166/9781789060225.

Fernandez-Cañero, R., Perez Urrestarazu, L. & Franco Salas, A. 2012 Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate. *Indoor and Built Environment* **21** (5), 642–650.

Fertilizers Europe 2017 *Industry Facts and Figures 2018*. Fertilizers Europe, asbl, Brussels, Belgium. Available from: http://fertilizerseurope.com/.

Finger, D., Wüest, A. & Bossard, P. 2013 Effects of oligotrophication on primary production in peri-alpine lakes: modeling primary production in lakes. *Water Resources Research* **49** (8), 4700–4710. https://doi.org/10.1002/wrcr.20355.

Garcia-Aguirre, J., Aymerich, E., González-Mtnez de Goñi, J. & Esteban-Gutiérrez, M. 2017 Selective VFA production potential from organic waste streams: assessing temperature and pH influence. *Bioresource Technology* **244**, 1081–1088. https://doi.org/10.1016/j.biortech.2017.07.187.

Gattringer, H., Claret, A., Radtke, M., Kisser, J., Zraunig, A., Rodriguez-Roda, I. & Buttiglieri, G. 2016 Novel vertical ecosystem for sustainable water treatment and reuse in tourist resorts. *International Journal of Sustainable Development and Planning* **11** (3), 263–274. https://doi.org/10.2495/SDP-V11-N3-263-274.

Goethem, C. V., Mertens, M., Cirujano, F. G., Seo, J. W., De Vos, D. & Vankelecom, I. F. J. 2018 Improved MOF nanoparticle recovery and purification using crosslinked PVDF membranes. *Chemical Communications* **54** (53), 7370–7373. https://doi.org/10.1039/C8CC04326D.

Green City Solutions 2019 *Green City Solutions*. Available from: https://greencitysolutions.de/en/.

Guardian 2019 From No Recycling to Zero Waste: How Ljubljana Rethought Its Rubbish. *The Guardian*, May 23, 2019, sec. Cities. Available from: https://www.theguardian.com/cities/2019/may/23/zero-recycling-to-zero-waste-how-ljubljana-rethought-its-rubbish.

Guenther, K., Heinke, V., Thiele, B., Kleist, E., Prast, H. & Raecker, T. 2002 Endocrine disrupting nonylphenols are ubiquitous in food. *Environmental Science & Technology* **36** (8), 1676–1680.

Hennebel, T., Boon, N., Maes, S. & Lenz, M. 2015 Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives. *New Biotechnology* **32** (1), 121–127. https://doi.org/10.1016/j.nbt.2013.08.004.

Hoelzle, R. D., Virdis, B. & Batstone, D. J. 2014 Regulation mechanisms in mixed and pure culture microbial fermentation. *Biotechnology and Bioengineering* **111** (11), 2139–2154. https://doi.org/10.1002/bit.25321.

Houston, J., Casazza, E., Briguglio, M. & Spiteri, J. 2018 *Enablers and Barriers to A Circular Economy*. R2PI H2020 Project Deliverable. Stakeholder Views Report. Available from: http://www.r2piproject.eu/wp-content/uploads/2018/08/R2pi-stakeholders-report-sept-2018.pdf.

Houzelot, V., Laubie, B., Pontvianne, S. & Simonnot, M.-O. 2017 Effect of up-scaling on the quality of ashes obtained from hyperaccumulator biomass to recover Ni by agromining. *Chemical Engineering Research and Design* **120**, 26–33. https://doi.org/10.1016/j.cherd.2017.02.002.

Houzelot, V., Ranc, B., Laubie, B. & Simonnot, M.-O. 2018 Agromining of hyperaccumulator biomass: study of leaching kinetics of extraction of nickel, magnesium, potassium, phosphorus, iron, and manganese from *Alyssum murale* ashes by sulfuric acid. *Chemical Engineering Research and Design* **129**, 1–11. https://doi.org/10.1016/j.cherd.2017.10.030.

IBA Hamburg GmbH 2013 *BIQ – Smart Material Houses*. Available from: https://www.iba-hamburg.de/projekte/bauausstellung-in-der-bauausstellung/smart-material-houses/biq/projekt/biq.html.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Istenič, D., Božič, G., Arias, C. A. & Griessler Bulc, T. 2017 Growth dynamic of three different white willow clones used in a zero-discharge wastewater treatment system in the sub-Mediterranean region – an early evaluation. *Desalination and Water Treatment* **91**, 260–267. https://doi.org/10.5004/dwt.2017.21186.

Istenič, D., Arias, C. A., Pavliha, G. & Griessler Bulc, T. 2018 Evapotranspiration and biomass production in a willow system under sub-Mediterranean climate. In: *IWA Conference Proceedings*, Valencia, Spain.

Jankowska, E., Chwialkowska, J., Stodolny, M. & Oleskowicz-Popiel, P. 2017 Volatile fatty acids production during mixed culture fermentation – the impact of substrate complexity and pH. *Chemical Engineering Journal* **326**, 901–910. https://doi.org/10.1016/j.cej.2017.06.021.

Kabir, E. R., Sharfin Rahman, M. & Rahman, I. 2015 A review on endocrine disruptors and their possible impacts on human health. *Environmental Toxicology and Pharmacology* **40** (1), 241–258. https://doi.org/10.1016/j.etap.2015.06.009.

Katsou, E., Nika, C.-E., Buehler, D., Maric, B., Megyesi, B., Mino, E., Almenar, J. B. & Bas, B. 2019 Transformation tools enabling the implementation of nature-based solutions for creating a resourceful circular city. *Blue-Green Systems*. https://doi.org/10.2166/bgs.2020.929.

Khan, M. I., Shin, J. H. & Kim, J. D. 2018 The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories* **17** (March). https://doi.org/10.1186/s12934-018-0879-x.

Kibler, K. M., Reinhart, D., Hawkins, C., Mohaghegh Motlagh, A. & Wright, J. 2018 Food waste and the food-energy-water nexus: a review of food waste management alternatives. *Waste Management* **74**, 52–62. https://doi.org/10.1016/j.wasman.2018.01.014.

Langergraber, G., Pucher, B., Simperler, L., Kisser, J., Katsou, E., Buehler, D., Garcia Mateo, M. C. & Atanasova, N. 2019 Implementing nature-based solutions for creating a resourceful circular city. *Blue-Green Systems* 2 (1), 173–185. https://doi.org/10.2166/bgs.2020.933.

Larsen, T. A. 2011 Redesigning wastewater infrastructure to improve resource efficiency. *Water Science and Technology* **63** (11), 2535–2541. https://doi.org/10.2166/wst.2011.502.

Larsen, T. A., Gebauer, H., Gründl, H., Künzle, R., Lüthi, C., Messmer, U., Morgenroth, E., Niwagaba, C. B. & Ranner, B. 2015 Blue diversion: a new approach to sanitation in informal settlements. *Journal of Water Sanitation and Hygiene for Development* **5** (1), 64–71. https://doi.org/10.2166/washdev.2014.115.

Lettinga, G., Van Velsen, A. F. M., Hobma, S. & De Zeeuw, W. 1981 Feasibility of anaerobic digestion for the direct treatment of, and the energy recovery from urban wastes. *Studies in Environmental Science* **9**, 97–109. https://doi.org/10.1016/S0166-1116(08)71356-6.

Li, Y. M., Chaney, R., Brewer, E., Roseberg, R., Angle, J. S., Baker, A., Reeves, R. & Nelkin, J. 2003 Development of a technology for commercial phytoextraction of nickel: economic and technical considerations. *Plant and Soil* **249** (1), 107–115.

Li, Y., Horsman, M., Wu, N., Lan, C. Q. & Dubois-Calero, N. 2008 Biofuels from microalgae. *Biotechnology Progress* **24** (4), 815–820. https://doi.org/10.1021/bp070371 k.

Logan, M. & Visvanathan, C. 2019 Management strategies for anaerobic digestate of organic fraction of municipal solid waste: current status and future prospects. *Waste Management & Research* **37** (1 suppl.), 27–39. https://doi.org/10.1177/0734242X18816793.

Madigan, M. T. & Jung, D. O. 2009 An overview of purple bacteria: Systematics, physiology, and habitats. In: *The Purple Phototrophic Bacteria*. Advances in Photosynthesis and Respiration (Neil Hunter, C., Daldal, F., Thurnauer, M. C. & Thomas Beatty, J., eds). Springer, Dordrecht, The Netherlands, pp. 1–15. https://doi.org/10.1007/978-1-4020-8815-5_1.

Malinska, K. & Zabochnicka-Swiatek, M. 2010 Biosystems for air protection. In: *Air Pollution* (Villanyi, V., ed.). InTech. https://doi.org/10.5772/10048.

Mansouri, S. S., Udugama, I. A., Cignitti, S., Mitic, A., Flores-Alsina, X. & Gernaey, K. V. 2017 Resource recovery from bio-based production processes: a future necessity? *Current Opinion in Chemical Engineering* **18**, 1–9. https://doi.org/10.1016/j.coche.2017.06.002.

Martí-Herrero, J., Soria-Castellón, G., Diaz-de-Basurto, A., Alvarez, R. & Chemisana, D. 2019 Biogas from a full scale digester operated in psychrophilic conditions and fed only with fruit and vegetable waste. *Renewable Energy* **133** (April), 676–684. https://doi.org/10.1016/j.renene.2018.10.030.

Mauky, E., Weinrich, S., Jacobi, H.-F., Nägele, H.-J., Liebetrau, J. & Nelles, M. 2017 Demand-driven biogas production by flexible feeding in full-scale – process stability and flexibility potentials. *Anaerobe* **46**, 86–95. https://doi.org/10.1016/j.anaerobe.2017.03.010.

Miklosi, A. 2013 *Chlorella Oxygen Pavilion Concept and the Symbiosis in Design*. Göteborgs Universitetsbibliotek, Gothenburg, Sweden. Available from: https://gupea.ub.gu.se/handle/2077/32306.

Mo, W. Y., Man, Y. B. & Wong, M. H. 2018 Use of food waste, fish waste and food processing waste for China's aquaculture industry: needs and challenge. *The Science of the Total Environment* **613–614**, 635–643. https://doi.org/10.1016/j.scitotenv.2017.08.321.

Morais, M. G. & Costa, J. A. V. 2007 Carbon dioxide fixation by *Chlorella kessleri, C. vulgaris, Scenedesmus obliquus* and *Spirulina* sp. cultivated in flasks and vertical tubular photobioreactors. *Biotechnology Letters* **29**, 1349–1352.

Murovec, B., Kolbl, S. & Stres, B. 2015 Methane yield database: online infrastructure and bioresource for methane yield data and related metadata. *Bioresource Technology* **189**, 217–223. https://doi.org/10.1016/j.biortech.2015.04.021.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Nehls, T., Jiang, Y., Dennehy, C., Zhan, X. & Beesley, L. 2015 From waste to value: urban agriculture enables cycling of resources in cities. In: *Urban Agriculture Europe* (Lohrberg, F., Licka, L., Scazzosi, L. & Timpe, A., eds). JOVIS, Berlin, Germany, pp. 170–173.

Ni, T. W., Staicu, L. C., Nemeth, R. S., Schwartz, C. L., Crawford, D., Seligman, J. D., Hunter, W. J., Pilon-Smits, E. A. H. & Ackerson, C. J. 2015 Progress toward clonable inorganic nanoparticles. *Nanoscale* **7** (41), 17320–17327. https://doi.org/10.1039/c5nr04097c.

Nordin, A. C. & Vinnerås, B. 2015 Sanitising black water by auto-thermal aerobic digestion (ATAD) combined with ammonia treatment. *Water Science and Technology* **72** (12), 2112–2121. https://doi.org/10.2166/wst.2015.432.

Nordin, A., Göttert, D. & Vinnerås, B. 2018 Decentralised black water treatment by combined auto-thermal aerobic digestion and ammonia – a pilot study optimising treatment capacity. *Journal of Environmental Management* **207**, 313–318. https://doi.org/10.1016/j.jenvman.2017.10.064.

O'Dwyer, E., Wang, H., Wang, A., Shah, N. & Guo, M. 2018 Optimisation of wastewater treatment and recovery solutions in industrial parks. *Computer Aided Chemical Engineering* **43**, 1407–1412. https://doi.org/10.1016/B978-0-444-64235-6.50246-1.

Osmani, M. & Bani, A. 2017 Heavy metals concentration of dumping site soils and their accumulation in Alyssum murale growing in selected dumping sites in Albania. *Thalassia Salentina* **39**. https://doi.org/10.1285/i15910725v39p83.

Osmani, M., Bani, A. & Hoxha, B. 2018a The phytomining of nickel from industrial polluted site of Elbasan-Albania. *European Academic Research* **V** (10). Available from: https://www.researchgate.net/publication/323457449_The_Phytomining_of_nickel_from_industrial_polluted_site_of_Elbasan-Albania.

Osmani, M., Bani, A., Gjoka, F., Pavlova, D., Naqellari, P., Shahu, E., Duka, I. & Echevarria, G. 2018b The natural plant colonization of ultramafic post-mining area of Përrenjas, Albania. *Periodico Di Mineralogia* **87** (2), 135–146. https://doi.org/10.2451/2018PM729.

Pandey, V. C. & Souza-Alonso, P. 2019 Market opportunities: in sustainable phytoremediation. In: *Phytomanagement of Polluted Sites* (Pandey, V. C. & Bauddh, K., eds). Elsevier, pp. 51–82. https://doi.org/10.1016/B978-0-12-813912-7.00002-8.

Pascual, A., De la Varga, D., Soto, M., Van Oirschot, D., Kilian, R. M., Álvarez, J. A., Carvalho, P., Brix, H. & Arias, C. A. 2018 Aerated constructed wetlands for treatment of municipal and food industry wastewater. In: *Constructed Wetlands for Industrial Wastewater Treatment* (Stefanakis, A. I., ed). John Wiley & Sons, Ltd, pp. 65–93. https://doi.org/10.1002/9781119268376.ch3.

Passos, F., Astals, S. & Ferrer, I. 2014 Anaerobic digestion of microalgal biomass after ultrasound pretreatment. *Waste Management* **34** (11), 2098–2103. https://doi.org/10.1016/j.wasman.2014.06.004.

Pettit, T., Irga, P. J. & Torpy, F. R. 2018 Towards practical indoor air phytoremediation: a review. *Chemosphere* **208**, 960–974. https://doi.org/10.1016/j.chemosphere.2018.06.048.

Plaza, M., Herrero, M., Cifuentes, A. & Ibáñez, E. 2009 Innovative natural functional ingredients from microalgae. *Journal of Agricultural and Food Chemistry* **57** (16), 7159–7170. https://doi.org/10.1021/jf901070 g.

Puyol, D., Batstone, D. J., Hülsen, T., Astals, S., Peces, M. & Krömer, J. O. 2017 Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects. *Frontiers in Microbiology* **7**. https://doi.org/10.3389/fmicb.2016.02106.

Raganati, F., Procentese, A., Olivieri, G., Russo, M. E., Salatino, P. & Marzocchella, A. 2014 MFA of clostridium acetobutylicum pathway: the role of glucose and xylose on the acid formation/uptake. *Chemical Engineering Transactions* **38**, 337–342.

Randall, D. G., Krähenbühl, M., Köpping, I., Larsen, T. A. & Udert, K. M. 2016 A novel approach for stabilizing fresh urine by calcium hydroxide addition. *Water Research* **95**, 361–369. https://doi.org/10.1016/j.watres.2016.03.007.

Razzak, S. A., Hossain, M. M., Lucky, R. A., Bassi, A. S. & de Lasa, H. 2013 Integrated CO_2 capture, wastewater treatment and biofuel production by microalgae culturing – a review. *Renewable and Sustainable Energy Reviews* **27**, 622–653. https://doi.org/10.1016/j.rser.2013.05.063.

Rijksdienst voor Ondernemend Nederland 2019 Greendeals. Available from: https://www.greendeals.nl/english.

Rodenas Motos, P., Ter Heijne, A., van der Weijden, R., Saakes, M., Buisman, C. H. & Sleutels, T. H. 2015 High rate copper and energy recovery in microbial fuel cells. *Frontiers in Microbiology* **6**, 527. https://doi.org/10.3389/fmicb.2015.00527.

Rodenas Motos, P., Molina, G., Ter Heijne, A., Sleutels, T., Saakes, M. & Buisman, C. 2017 Prototype of a scaled-up microbial fuel cell for copper recovery. *Journal of Chemical Technology and Biotechnology* **92** (11), 2817–2824. https://doi.org/10.1002/jctb.5353.

Saadiah, H., Aini, N., Rahman, A., Kalsom, U., Baharuddin, S. & Ari, A. B. 2017 Feasibility of using kitchen waste as future substrate for bioethanol production: a review. *Renewable and Sustainable Energy Reviews* **74**, 671–686. https://doi.org/10.1016/j.rser.2017.02.071.

Senecal, J. & Vinnerås, B. 2017 Urea stabilisation and concentration for urine-diverting dry toilets: urine dehydration in ash. *Science of the Total Environment* **586**, 650–657. https://doi.org/10.1016/j.scitotenv.2017.02.038.

Sharkey, T. D., Wiberley, A. E. & Donohue, A. R. 2008 Isoprene emission from plants: why and how. *Annals of Botany* **101** (1), 5–18. https://doi.org/10.1093/aob/mcm240.

Sigma-Aldrich 2018 *Ammonium Nickel(II) Sulfate Hexahydrate*. Available from: https://www.sigmaaldrich.com.

Simha, P., Senecal, J., Nordin, A., Lalander, C. & Vinnerås, B. 2018 Alkaline dehydration of anion-exchanged human urine: volume reduction, nutrient recovery and process optimisation. *Water Research* **142**, 325–336. https://doi.org/10.1016/j.watres.2018.06.001.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Simonnot, M.-O., Vaughan, J. & Laubie, B. 2018 Processing of bio-ore to products BT. In: *Agromining: Farming for Metals: Extracting Unconventional Resources Using Plants* (Van der Ent, A., Echevarria, G., Baker, A. J. M. & Morel, J. L., eds). Springer International Publishing, Cham, Switzerland, pp. 39–51. https://doi.org/10.1007/978-3-319-61899-9_3.

Singh, S., Rinta-Kanto, J. M., Kettunen, R., Lens, P., Collins, G., Kokko, M. & Rintala, J. 2019 Acetotrophic activity facilitates methanogenesis from LCFA at low temperatures: screening from mesophilic inocula. *Archaea* 1–16. https://doi.org/10.1155/2019/1751783.

Slavov, A. K. 2017 General characteristics and treatment possibilities of dairy wastewater – a review. *Food Technology and Biotechnology* **55** (1), 14–28. https://doi.org/10.17113/ft b.55.01.17.4520.

Song, X., Luo, W., Hai, F. I., Price, W. E., Guo, W., Ngo, H. H. & Nghiem, L. D. 2018 Resource recovery from wastewater by anaerobic membrane bioreactors: opportunities and challenges. *Bioresource Technology* **270**, 669–677. https://doi.org/10.1016/j.biortech.2018.09.001.

Stichting Toegepast Onderzoek Waterbeheer - Rijkskantoor Rijnstraat 8. Saniwijzer 2017 Available from: https://www.saniwijzer.nl/projecten/rijkskantoor-rijnstraat-8/detail=94 (accessed 3 April 2019).

Strazzera, G., Battista, F., Herrero Garcia, N., Frison, N. & Bolzonella, D. 2018 Volatile fatty acids production from food wastes for biorefinery platforms: a review. *Journal of Environmental Management* **226**, 278–288. https://doi.org/10.1016/j.jenvman.2018.08.039.

Su, Y. M. & Lin, C. H. 2015 Removal of indoor carbon dioxide and formaldehyde using green walls by bird nest fern. *Horticulture Journal* **84** (1), 69–76.

Sulonen, M. L. K., Kokko, M. E., Lakaniemi, A.-M. & Puhakka, J. A. 2018 Simultaneous removal of tetrathionate and copper from simulated acidic mining water in bioelectrochemical and electrochemical systems. *Hydrometallurgy* **176**, 129–138. https://doi.org/10.1016/j.hydromet.2018.01.023.

Tamis, J., Mulders, M., Dijkmans, H., Rozendal, R., van Loosdrecht, M. C. M. & Kleerebezem, R. 2018 Pilot-scale polyhydroxyalkanoate production from paper mill wastewater: process characteristics and identification of bottlenecks for full-scale implementation. *Journal of Environmental Engineering* **144** (10), 04018107. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001444.

Tang, J., Zhang, C., Shi, X., Sun, J. & Cunningham, J. A. 2019 Municipal wastewater treatment plants coupled with electrochemical, biological and bio-electrochemical technologies: opportunities and challenge toward energy self-sufficiency. *Journal of Environmental Management* **234**, 396–403. https://doi.org/10.1016/j.jenvman.2018.12.097.

Techmetall 2019 *grünwand Klimafassade*. Available from: https://gruenwand.com/.

Trulli, E., Ferronato, N., Torretta, V., Piscitelli, M., Masi, S. & Mancini, I. 2018 Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates. *Waste Management* **71**, 556–564. https://doi.org/10.1016/j.wasman.2017.10.018.

Udert, K. M. & Wächter, M. 2012 Complete nutrient recovery from source-separated urine by nitrification and distillation. *Water Research* **46** (2), 453–464. https://doi.org/10.1016/j.watres.2011.11.020.

Uwizeye, M. L., Venditti, S. & Hansen, J. 2017 Selection criteria of Microthrix parvicella as lipid accumulator in activated sludge treatment plants. In: *IWA YWP Conference BeNeLux 2017*, Luxembourg.

Van der Roest, H., Van Loosdrecht, M., Langkamp, E. J. & Uijterlinde, C. 2015 Recovery and reuse of alginate from granular Nereda sludge. *Water* **21**, 48.

Vlaeminck, S. E., Terada, A., Smets, B. F., Van der Linden, D., Boon, N., Verstraete, W. & Carballa, M. 2009 Nitrogen removal from digested black water by one-stage partial nitritation and anammox. *Environmental Science & Technology* **43** (13), 5035–5041. https://doi.org/10.1021/es803284y.

VUNA GmbH 2019 Available from: http://vuna.ch/.

Wang, H., Xu, J. & Sheng, L. 2019 Study on the comprehensive utilization of city kitchen waste as a resource in China. *Energy* **173**. https://doi.org/10.1016/j.energy.2019.02.081.

Waterschap Rijn en IJssel 2018 *Kaumera* (blog). Available from: https://kaumera.com/english/kaumera/.

Wei, X., Lyu, S., Yu, Y., Wang, Z., Liu, H., Pan, D. & Chen, J. 2017 Phylloremediation of air pollutants: exploiting the potential of plant leaves and leaf-associated microbes. *Frontiers in Plant Science* **8**. https://doi.org/10.3389/fpls.2017.01318.

Weißbach, M., Thiel, P., Drewes, J. E. & Koch, K. 2018 Nitrogen removal and intentional nitrous oxide production from reject water in a coupled nitritation/nitrous denitritation system under real feed-stream conditions. *Bioresource Technology* **255**, 58–66. https://doi.org/10.1016/j.biortech.2018.01.080.

Weithmann, N., Möller, J. N., Löder, M. G. J., Piehl, S., Laforsch, C. & Freitag, R. 2018 Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Science Advances* **4** (4), eaap8060. https://doi.org/10.1126/sciadv.aap8060.

Wit, J. B. d., de Graaf, R., Elzinga, N., Debucquoy, W., ‘t Lam, G. P., Rodenhuis, J., Stutterheim, E. & Piekema, L. 2018 *Evaluatie Nieuwe Sanitation Noorderhoek/Waterschoon 2 (Evaluation New Sanitation Noorderhoek/Waterschoon 2)*. STOWA, Amersfoort, The Netherlands.

Wolverton, B. C. & McDonald, C. R. 1983 *Microbial Filters and Higher Plants for Treating Hazardous and Toxic Chemicals.* Available from: http://airex.tksc.jaxa.jp/pl/dr/19930073014/en.

Wolverton, B. C. & McDonald-McCaleb, R. C. 1986 *Biotransformation of Priority Pollutants Using Biofilms and Vascular Plants*. EPA/600/J-86/310. U.S. Environmental Protection Agency, Washington, DC, USA. Available from: http://ntrs.nasa.gov/search.jsp?N=0&Ntk=all&Ntx=mode matchall&Ntt=20050236283.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user

Wolverton, B. C. & Wolverton, J. D. 1993 Apparatus for purifying waste water and air in an indoor environment, issued 1993. United States Patent US5269094A. Available from: http://www.google.com/patents?hl=en&lr=&vid=USPAT5269094&id=KIwlAAAAEBAJ&oi=fnd&dq=Apparatus+for+purifying+waste+water+and+air+in+an+indoor+environment&printsec=abstract.

Wood, R. A., Burchett, M. D., Alquezar, R., Orwell, R. L., Tarran, J. & Torpy, F. 2006 The potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-study. *Water, Air, and Soil Pollution* **175** (1–4), 163–180. https://doi.org/10.1007/s11270-006-9124-z.

World Bank 2017 *Urban Development Overview*. World Bank, Washington, DC, USA. Available from: http://www.worldbank.org/en/topic/urbandevelopment/overview.

World Health Organization 2011 *WHO Guidelines for Drinking-Water Quality*. World Health Organization, Geneva, Switzerland. Available from: https://books.google.com/books?hl=de&lr=&id=SJ76COTm-nQC&oi=fnd&pg=PR15&dq=WHO+Guidelines+for+Drinking-water+Quality:+Recommendations&ots=V7sXreT8Yg&sig=qjy6jMaeBxK-nkvotmfipoZudZg.

Wuang, S. C., Khin, M. C., Chua, P. Q. D. & Luo, Y. D. 2016 Use of *Spirulina* biomass produced from treatment of aquaculture wastewater as agricultural fertilizers. *Algal Research* **15**, 59–64. https://doi.org/10.1016/j.algal.2016.02.009.

Xu, Z., Wang, L. & Hou, H. 2011 Formaldehyde removal by potted plant-soil systems. *Journal of Hazardous Materials* **192** (1), 314–318. https://doi.org/10.1016/j.jhazmat.2011.05.020.

Zacharof, M.-P. & Lovitt, R. W. 2014 Recovery of volatile fatty acids (VFA) from complex waste effluents using membranes. *Water Science and Technology* **69** (3), 495–503. https://doi.org/10.2166/wst.2013.717.

Zeeman, G. 2012 *New Sanitation: Bridging Cities and Agriculture*. Wageningen University, Wageningen, The Netherlands.

Zeeman, G., Kujawa, K., de Mes, T. Z. D., de Graaff, M. S., Abu-Ghunmi, L. N. A. H., Mels, A. R., Meulman, B., Temmink, H., Buisman, C., van Lier, J. & Lettinga, G. 2008 Anaerobic treatment as a core technology for energy, nutrients and water from source-separated domestic waste(water). *Water Science and Technology* **57** (8), 1207–1212.

Zhang, X., Laubie, B., Houzelot, V., Plasari, E., Echevarria, G. & Simonnot, M.-O. 2016 Increasing purity of ammonium nickel sulfate hexahydrate and production sustainability in a nickel phytomining process. *Chemical Engineering Research and Design* **106**, 26–32. https://doi.org/10.1016/j.cherd.2015.12.009.

Zraunig, A., Estelrich, M., Gattringer, H., Kisser, J., Langergraber, G., Radtke, M., Rodriguez-Roda, I. & Buttiglieri, G. 2019 Long term decentralized greywater treatment for water reuse purposes in a tourist facility by vertical ecosystem. *Ecological Engineering* **138**, 138–147. https://doi.org/10.1016/j.ecoleng.2019.07.003.

Downloaded from http://iwaponline.com/bgs/article-pdf/2/1/138/740604/bgs0020138.pdf
by Wageningen University & Research – Library user