Validated innovative approaches for energy-efficient resource recovery and re-use from municipal wastewater: from anaerobic treatment systems to a biorefinery concept

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Abstract

The development of innovative technologies in wastewater treatment create the concept of biorefinery in wastewater treatment plants (WWTPs), placing anaerobic processes in the highlight. Starting from the conventional anaerobic treatment processes to “closing the loop” scheme, next generation WWTPs are ready to serve for water, energy and materials mining. While bioenergy is still dominating the resource recovery, recovery of value-added materials (i.e. struvite, biopolymers, cellulose) are receiving significant attention in recent years. So, what are the state-of-the-art approaches for energy-efficient resource recovery and re-use from municipal wastewater? This paper follows a critical review on the validated technologies in operational environment available and further suggests possible market routes for the recovered materials in WWTPs. Considering the development and verification of a novel technology together with the valorisation of the obtained products, biorefinery and resource recovery approaches were gathered in this review paper from a circular economy point of view. General currently-faced barriers were briefly addressed to pave the way to a create to-the-point establishments of resource recovery facilities in the future.

Keywords: anaerobic treatment, biorefinery, energy recovery, material recovery, municipal wastewater, valorisation

1. Introduction

During the last years, wastewater treatment plants (WWTP) have moved from the concept of "waste treatment", aimed at discharging treated wastewater into surface waters, to the concept of "water resource recovery facility" (WRRF). This transformation from pollutants removal to valuable resources frames wastewater management in the broader context of the circular economy. The question that arises is which are the possible recovered and safely reusable resources to help closing the loop in WRRF?

First of all, the reclaimed water: Water reuse is particularly important because it is considered as an effective approach to address water shortage problems and water quality deterioration issues (Sun et al. 2016). Water reuse can be one of the methods of recycling treated wastewater for beneficial purposes, such as agricultural and landscape irrigation, industrial processes, non-potable domestic use (e.g. toilet flushing), and groundwater replenishing. At EU level the minimum quality standards for water reuse have been proposed in May 2018; this proposal for regulation lays down minimum requirements for water quality and monitoring and the obligation to carry out specified key risk management tasks. Classes of reclaimed water quality, minimum treatment requirements, allowed uses, irrigation methods and minimum requirements for water quality are set (http://www.europarl.europa.eu/RegData/etudes/BRIE/2018/625171/EPRS_BRI(2018)625171_EN.pdf).

On site energy recovery, particularly as biogas production, in WWTP is widely diffused as an alternative source of energy, for the recovery of thermal, electrical and mechanical energy, to be consumed either inside (also achieving energy self-sufficiency) or outside the plant. Nowadays energy recovery takes place mostly in the sludge line and actions in water line are much rarer but more and more of interest (Papa et al. 2017). Biogas is the main resource of anaerobic treatment systems. In the last years; however, two-step bioconversion comes into prominence as more value is derived to volatile fatty acids (VFAs) production before ending up to other end-products. Moreover, anaerobic processes offer much more than conventional wastewater treatment, provide recovering sustainable energy and valuable biochemicals. This scenario helps to recognize conventional and innovative (i.e. anaerobic membrane bioreactor - AnMBR) anaerobic processes as core of biorefinery general concept (Puyol et al., 2017, Krzeminski et al., 2017).

Nutrient recovery and recycling take an important role in circular economy. Recovered nutrients from the wastewater can be utilized as soil amendments or fertilizers for beneficial uses in agriculture. In particular, NH_4^+ form is advantageous because it predominates in anaerobic reactor effluents and can be useful for fertigation purposes. Phosphorus recovery (i.e. in the form struvite or phosphorous salts) becomes essential for preventing eutrophication in the aquatic environment and for alleviating economic dependence on phosphate rocks. Addressing raw materials conservation, arising from phosphorus scarcity is described as one of the greatest global challenges of the 21st Century (Peng et al. 2018).

The resources mentioned above are those most commonly recovered in WWTPs; in addition to them there are more innovative ones that can be originated from cellulosic primary sludge (CPS) and polyhydroxyalkanoate (PHA) rich sludge. The cellulosic sludge can be separated by upstream dynamic sieving. The CPS can then be anaerobically digested to produce biogas, or, under optimal acidogenic fermenting conditions it produces VFAs. Here the propionate content can be more than 30% and can optimize the enhanced biological phosphorus removal (BPR) processes (Crutchik et al. 2018). Long-term operation indicated that anaerobic alkaline fermentation for VFA production from sewage sludge is both technically and economically feasible (Liu et al., 2018). Regarding PHA recovery, primary and secondary sewage sludges are potential feedstock for its recovery (Kumar et al. 2018). PHAs have comparable properties to petrochemical plastics and can also serve as a biofuel or building blocks for the synthesis of various chemicals (Kleerebezem et al. 2015).

While some of the above-mentioned reuse and recovery approaches towards wastewater are already efficiently implemented, some of them still lack the convenient technology together with social-technological planning and design methodology to identify their potential end-use and market requirements (Van Der Hoek et al. 2016).

At European level there are several EU projects founded by Horizon 2020 that aim at recovering materials from centralized and decentralized WWTPs. For example, SMART-Plant is an Innovation Action that aims at reducing the energy and environmental footprint and, contemporary, at recovering valuable materials (SMART-Products are water, cellulose, biopolymers, nutrients) that are valued in construction, chemical and agriculture supply chain (smart-plant.eu). POWERSTEP is another Innovation Action aims at energy positive WWTP, biogas production and carbon extraction (powerstep.eu). P-REX, similarly, aimed at sustainable sewage sludge management promoting phosphorus recycling and energy efficiency (p-rex.eu).

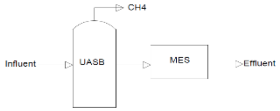
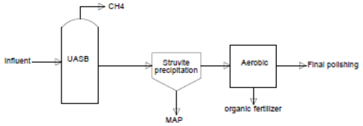
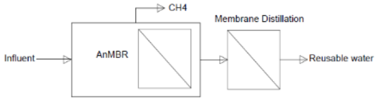
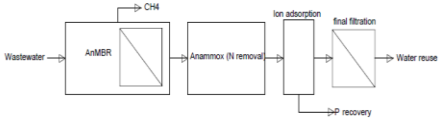
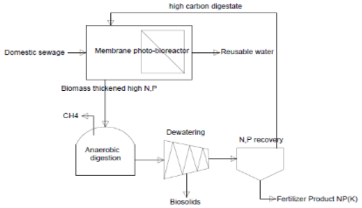
This review critically analyses innovative anaerobic processes to recover materials and energy from municipal wastewater, state of the art WWTPs and future aspects. The energy-efficient resource recovery is examined by the critical analysis only of the anaerobic processes. Moreover, the discussed technologies are selected based on the validation criteria of the demonstrative or full scales applications to ensure the robustness of the technologies supporting the characteristics, as quantity and quality, of the products to be marketed. Hence, this review paper aims to provide a comprehensive overview to the biorefinery concept, recent leading technologies and further sustainable scenarios to fulfil circular economy goals. Although great previous efforts have been done towards anaerobic processes and the concept of resource recovery, environmental technology verification (ETV) has further reviewed innovative technologies together with the possible valorisation market alternatives, bottlenecks or barriers of recovered products.

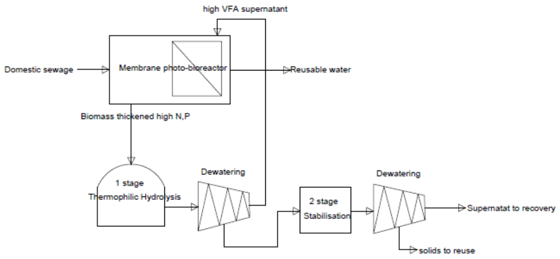
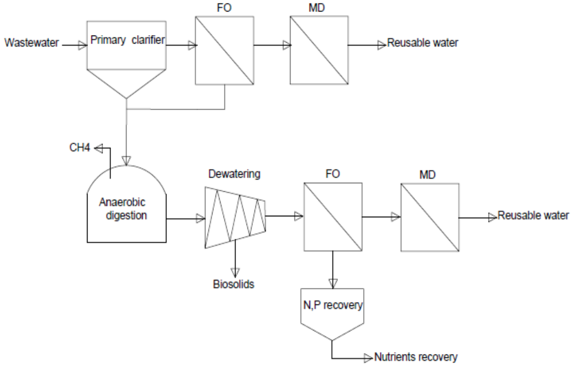
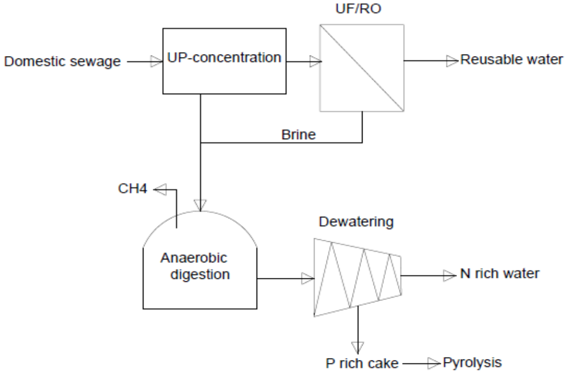
2. Brief evolution of anaerobic schemes as the core of the biorefinery approach

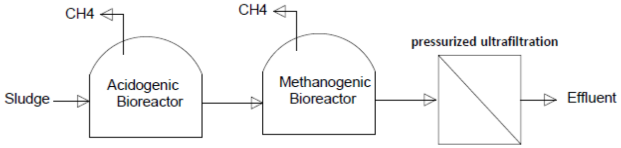
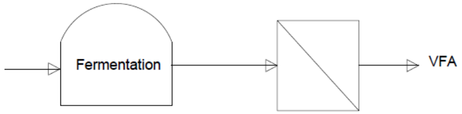
Anaerobic treatment is one of the most promising treatment technologies for developing more sustainable sanitation; it is considered to be the core technology for resource and energy recovery (Stazi and Tomei 2018). Upflow anaerobic sludge blanket (UASB) was successfully implemented and established within a wide acceptance in municipal WWTPs, especially in tropical and subtropical regions where the temperature of the wastewater is usually above 20 ^{o}C (Lohani et al. 2016). Expanded granular sludge bed (EGSB) was further developed to enhance substrate-biomass interaction within the treatment system by expanding the sludge bed and increasing hydraulic mixing compared to UASB (Niwa et al. 2016; Cuff et al. 2018). Although well-established UASB and/or EGSB configurations mostly meet the requirements necessary for anaerobic treatment, unfavourable conditions regarding the disintegration of granules led to the development of AnMBR by coupling membrane technology with anaerobic treatment. Meanwhile, combined heat and power (CHP) systems using the anaerobic digestion (AD) of sludge has become the most adopted technology in the existing energy self-sufficient WWTPs. Based on life cycle comparison, AnMBR technology was found to produce more net energy as biogas compared to conventional activated sludge coupled with AD (Gu et al. 2017). The main advantage of AnMBR as a mainline wastewater treatment process is the capacity to recover most of the energy potential in the wastewater rather than the fraction currently recovered by the aerobic-anaerobic treatment. The recent results obtained from pilot-scale AnMBRs treating domestic wastewaters were reviewed and discussed in detail (Shin and Bae 2018).

Table 1 provides a schematic representation of different flow schemes to enhance the role of anaerobic processes as core of biorefinery approach. Table 2 refers to resource recovery associated with the schemes in Table 1; all of them recover methane, which is the main produced-resource in WWTPs where anaerobic processes are implemented. Moreover, some of them recover N, P and VFAs due to coupling with the membrane technology. The optimization of anaerobic processes brings the key towards energy self-sufficient WWTPs.

Table 1. Flow schemes with resource recovery - role of anaerobic processes

Main units	Scheme and resource recovery	Anaerobic process	Reference	Number scheme
Anaerobic Process + Post-treatment		UASB in main line	(Li and Yu 2016)	1a*
		UASB in main line	(Verstraete et al. 2009)	1b*
AnMBR + Post-treatment		AnMBR in main line	(Song et al. 2018)	2a*
		AnMBR in main line	(Batstone and Virdis 2014)	2b*
Aerobic Membrane + AD + dewatering		AD in sludge line	(Batstone et al. 2015)	3a*

		Double stage AD in sludge line	(Batstone et al. 2015)	3b*
Membrane (double stage) + AD + dewatering		AD in sludge line	(Ansari et al. 2017)	4a**
		AD in sludge line	(Verstraete et al. 2009)	4b**

AD/Fermentation + Membrane		AD in sludge line	(Joo et al. 2016)	5a**
		Fermentation in sludge line	(Longo et al. 2015)	5b**

Legend: MES=microbial electrochemical systems; MAP= magnesium ammonium phosphate; MD=membrane distillation, UF=ultrafiltration; RO=reverse osmosis; FO= forward osmosis; VFA=volatile fatty acids. *Lab/Pilot scale; **Pilot/demonstrative scale

Table 2. Resource recovery for different plant schemes.

Resource recovery	Item	Scheme numbers
Methane	CH_4	1,2,3,4,5
Water Reuse	WR	2,3,4
VFA	VFA	5b
N rich sludge	NS	3,4
P rich sludge	PS	3,4
N rich water	NW	4
P rich water	PW	None
Struvite	MAP	1b

3. Resource recovery in anaerobic processes

3.1. Wastewater treatment line

The biogas produced during anaerobic treatment of wastewater can be utilized as an energy source (Table 3). However, a significant amount of methane cannot be recovered since a major proportion is dissolved in the effluent, even if the biogas exhibits high CH_4 content (Liu et al., 2018; Souza et al., 2011). Anaerobic wastewater treatment processes such as UASB is therefore limited because of low liquid upflow velocity and inadequate mixing (Yeo and Lee 2013). CH_4 losses recorded in different anaerobic reactors at a pilot-scale were listed and discussed and average CH_4 loss in the effluents were stated between 19-85% (Crone et al. 2017). In municipal wastewater treatment up to 30-40% of the produced methane was reported to be loss in the application of AnMBR (Krzeminski et al. 2017). Although many efforts were directed towards recovering dissolved CH_4 from anaerobic effluents, such as hollow fibre membrane contactors (Cookney et al. 2016) or down-flow hanging sponge reactors (Hatamoto et al. 2011), scaling up is still missing and validation is required.

In the concept of valorisation of municipal wastewater, two-step bioconversion stands as an attractive alternative route (Li and Yu 2011) in the fermentation reactors (Table 3). Complex organic matter in wastewater is simply converted to VFAs before ending up as other valuable end-products (Zhou et al. 2018). This allows a separated optimization of bioconversion mechanisms into a more straightforward bioproduction process (Pan et al. 2018). The concentration and speciation of VFAs during this process often determines the desired quality of the end-products (Reyhanitash et al. 2017).

Although VFAs are so-called intermediate products, they have various potential applications within the WWTP. Acetate is the most-preferred VFA product for denitrification within WWTP followed by butyrate and propionate (Elefsiniotis and Wareham 2007). Propionate can enhance BPR processes in biological nutrient removal systems (Chen et al. 2004). However, further application, either within WWTP or the product value, will determine the desired VFA concentration and speciation (Peces et al. 2016) as discussed in the following section. Microbial fuel cells (MFCs) is also another option to produce electricity from VFAs by fermentative hydrogen production (Teng et al. 2010); however, this technology has not yet been validated. Low power density and high operating cost of MFCs limits their implementations on a large-scale (He et al. 2017).

AnMBRs have been successfully implemented to treat municipal wastewaters with high COD removal rates for the main water reuse purpose. However, the discharge of the treated effluents into the aquatic environment or water reuse is usually not possible without further nutrient removal (Ruiz-Martinez et al. 2012; Batstone et al. 2015). In this regard, nutrient removal from AnMBR effluent using microalgae was proposed (Viruela et al. 2016). In addition, within the context of EU LIFE Project MEMORY (life-memory.eu), submerged AnMBR was demonstrated to combine AD and membrane technology. Such innovative pilot-scale implementations suggest promising technologies for municipal wastewater treatment and resource recovery (https://ec.europa.eu/info/research-and-innovation/law-and-regulations/identifying-barriers-innovation_en).

Table 3. Recovered products in anaerobic wastewater line.

Wastewater line	Influent	Scale	Volume	HRT	OLR	T	Recovered products	Amounts/Composition	Location	Reference
Process			m^3xline	h	kg COD/m^3/d	°C				
Fermentation reactor	sewage WW	Pilot	0.5	4.6–5.9 (d)		35	VFA	7453 mg COD/L	Italy	(Longo et al. 2015)
Fermentation reactor	sewage WW	Pilot	1			42	VFA	120 mg VFA/g VS/d	Belgium	(Morgan-Sagastume et al. 2015)
Fermentation reactor	sewage WW	Pilot	0.05	8 (d)		25	VFA	2825 mg COD/L	China	(Li et al. 2011)
UASB	sewage WW	Full	605x8	8			CH_4	390.1 Nm^3/d, 78.2% CH_4	Brazil	(Rosa et al. 2018)
UASB	sewage WW	Pilot	0.12	4		24	CH_4	0.072 L CH_4/g $COD_{removed}$	Brazil	(Barbosa and Sant’Anna 1989)
UASB	sewage WW	Pilot	20.36	10	0.5	20	CH_4	0.3-0.9 Nm^3/d, 78% CH_4	Spain	(Álvarez et al. 2008)
UASB	sewage WW	Pilot	0.021	4.7			CH_4	0.22 L CH_4/g $COD_{removed}$		(Uemura and Harada 2000)
UASB	sewage WW	Pilot	0.11	9	0.73	25	CH_4	212 L CH_4/g $COD_{removed}$		(Agrawal et al. 1997)
UASB	sewage WW	Full	14	12	0.88		CH_4	0.24 L CH_4/g $COD_{removed}$	Brazil	(Souza et al. 2011)
UASB	sewage WW	Pilot	0.36	5	2.12	25	CH_4	0.22 L CH_4/g $COD_{removed}$	Brazil	(Souza et al. 2011)
UASB	sewage WW	Full	1200	6	2.35	25	CH_4	0.075 L CH_4/g $COD_{removed}$	India	(Draaijer et al. 1992)

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Table 4. Recovered products in anaerobic sludge line

Sludge line	Influent	Scale	Flow	Volume	HRT	OLR	T	Residual concentrations/Recovered products	Amount	Location	Reference
Process			t/d	m3xline	d	kg VS/m^3/d	°C	°C			
FERM	WAS	Full		30		3	35	VFA	1261 kg VFA/d	Wuxi city of China	(Liu et al., 2018)
FERM+AD	Cellulosic PS	Pilot	n.a	n.a.	n.a		n.a.	VFA	100-120 mg COD/g VS·d	Verona, Italy	(Crutchik et al. 2018)
								Struvite	0.15 kg struvite per capita/year		
								CH_4	n.a.		
AD	PS+WAS	Full	n.a	4400x2	20	1-2	M	Electricity	25-55% $COD_{converted}$	Tilburg-Noord, Netherlands	(De Vrieze et al. 2016)
								Ammonia	143 kg N/d		
								Struvite	36 kg P/d		
AD	WAS	Full	n.a	2900	25	1-2	M	Electricity	38% $COD_{converted}$	Land van Cuijk, Netherlands	(De Vrieze et al. 2016)
								Ammonia	175 kg N/d		
								Struvite	137 kg P/d		
AD	PS+WAS	Full	n.a	5430x2	20	1-2	M	Electricity	0.82 m^3 CH_4/m^3/d , 25-55%$COD_{converted}$	Bath, Netherlands	(De Vrieze et al. 2016)
								Ammonia	440 kg N/d		
								Struvite	112 kg P/d		
AD	WAS	Full	n.a	12000x6	20		M	Biogas	0.4 m^3 biogas/VSS	Castiglione Torinese, Italy	(Traversi et al. 2015)
AD	PS+WAS	Full	n.a	12000x6	25		M	Biogas	0.49 m^3 biogas/VSS	Castiglione Torinese, Italy	(Traversi et al. 2015)
TH+AD	Sewage sludge	Full	n.a	100	15-18	3.5	55	CH_4	0.35 m^3 CH_4/kg VS	Namyangju city, Korea	(Han et al. 2017)
Co-DA	PS+WAS+OFMSW	Full	n.a	n.a.	45	1.3	35	Electricity	400 kW	Rovereto,Italy	(Nghiem et al. 2017)
Co-DA	PS+WAS+OFMSW	Full	120	n.a.		0.78	70	Electricity	125 kW	Treviso,Italy	(Nghiem et al. 2017)
Co-DA	PS+WAS+OFMSW	Full	95	n.a.		n.a.	55	Electricity	95 kW	Kurobe, Japan	(Nghiem et al. 2017)
Co-DA	PS+WAS+OFMSW	Full	2700	n.a.	18	n.a.	35	Electricity	11000 kW	East Bay MUD, USA	(Nghiem et al. 2017)

3.2. Sludge treatment line

Sewage sludge management constitutes a major part of the operating expenses of municipal WWTPs. In full-scale WWTPs sewage sludge usually undergoes anaerobic digestion to recover energy (CH_4-rich biogas), and thus produce heat and electricity within the concept of combined heat and power plants. There is also a growing trend to use sludge as a feedstock in other value-added processes together with bioenergy (Zacharof and Lovitt, 2013) as shown in Table 4.

3.2.1 Recovered materials: VFA

More attention has been paid in the recent years to recover VFAs through the acidogenic fermentation of sewage sludge on down-stream processes (Liu et al. 2012; Longo et al. 2015). In a wider biorefinery concept, carbon upgrading to VFAs seems an energy-efficient and cost-effective strategy. However, utmost importance lies here when considering the WWTP as an integrated process, since extracting VFA will reduce the amount of organic matter fed to AD, which will eventually decrease the energy recovery (Peces et al. 2016). In this regard, the benefits of VFA production and extraction from sewage sludge should be well-designed and optimized in order not to outshadow methane recovery. The optimization should focus on two main criteria: (i) the cost (capital investment and operating expenses) of the fermentation and extraction process and further earnings from VFA use or sale; and (ii) the impact on CH_4 generation (Peces et al. 2016).

Depending on the selective production of VFAs from the acidogenic fermentation of sewage sludge, VFAs also have high economic values such as materials used in the production of bioplastics and biotextiles (Zacharof and Lovitt 2013; Lin et al. 2018). For instance, acetate and butyrate are preferred for polyhydroxybutyrate (PHB) production, while propionate is required when producing polyhydroxyvalerate (PHV) (Shen et al. 2014; Peces et al. 2016). In addition, some important characteristics such as higher flexibility, low stiffness and brittleness, and higher tensile strength and toughness are highlighted to promote the production of co-polymers using VFAs with higher propionate/acetate ratio (Frison et al. 2015; Crutchik et al. 2018). However, establishing consistence VFA concentrations and proportion remains a significant challenge.

3.2.2 Recovered materials: Nutrients

As mentioned earlier, there is large interest in decreasing costs and elevating sustainability by energy-efficient resource recovery in the concept of biorefinery (Raheem et al. 2018). So far, validated biorefinery products from WWTPs include nutrients (i.e. N, P), biopolymers (i.e. PHA) and cellulose (Zijp et al. 2017; Raheem et al. 2018).

The recovered nutrients from WWTPs can be utilized for struvite and/or Ca-P precipitation (Cieślik and Konieczka 2017; Melia et al. 2017) or biochar adsorption (Huggins et al. 2016). Struvite ($MgNH_4PO_4$) crystallization has been successfully used for simultaneous recovery of nutrients from wastewater (Hermassi et al. 2018) together with calcium phosphate ($Ca_3(PO_4)_2$) (Le Corre et al. 2009). Struvite is more preferred in agricultural use due to the fact that magnesium (Mg), N and P are released simultaneously (1:1:1 M ratio), and that the rate of nutrient release is slow compared to other fertilizers (Puchongkawarin et al. 2015). Deficient concentrations of phosphorus, on the other hand, limit the struvite precipitation. Even the presence of toxic compounds and/or micropollutants in wastewater restrain its purity and further agricultural application. Hence, alternative nutrient recovery technologies (i.e. membrane, electrodialysis) should be considered to improve the quality of the recovered nutrients (Xie et al. 2016). Several other benefits are also associated with P recovery by crystallization. For instance, the volume of the sludge produced together with other undesired precipitates diminishes, which eventually decreases the cost of sludge disposal (Hermassi et al. 2018). Integration of the Short Cut Enhanced Nutrient Abatement (SCENA) system into the Carbonera WWTP, Italy, was previously evaluated (Longo et al. 2017) and the results motivated the Horizon 2020 ‘SMART-Plant’ action which is currently running and investigates the optimization of the best scenario for SCENA within SMARTech4a and SMARTech4b. Briefly, the SCENA system integrates the following processes: optional upstream concentration of cellulosic sludge, fermentation of dynamic thickened sewage sludge to produce VFAs as carbon source, and nitrogen and phosphorus removal (by P-bioaccumulation) via nitrite from sludge reject water using an SBR. In this configuration, nitrogen is removed through the bioprocesses of nitritation/denitritation, and Enhanced

BPR (EBPR) via nitrite using the VFAs from sludge fermentation liquid as carbon source. SMARTech4b is another validated SCENA pilot-scale system at the WWTP of Psyttalia, Greece. It enables the integration of the enhanced biogas recovery (by thermal pressure hydrolysis) of sewage sludge with side stream energy-efficient and compact nitrogen removal and phosphorus recovery. The CAMBI™ thermal hydrolysis process has been installed to treat 50% of the produced sludge before this is sent for AD. The integration of CAMBI™ with anaerobic digestion produces, after dewatering, a reject water stream that has a very high ammonium nitrogen concentration (>1.2 gN/L) to be removed in the SCENA unit.

Furthermore, many technologies are applied in full size for specific objective of phosphorous salts recovery. In fact, CalPrex^{TM} reactor (Pre-digestion P-recovery) placed between the acid phase and gas phase digesters enables dissolved phosphorus in dewatered centrate precipitates and is recovered as a brushite crystal. Similarly, the AirPrex^{TM} reactor (Sludge optimization and P-recovery) placed between the anaerobic digester and the dewatering equipment converts the orthophosphate into struvite crystals, which are harvested from the bottom of the reactor. Both the WASSTRIP^{TM} and Ostara Pearl^{TM} processes are already in operation in a number of municipal installations and achieve efficient P recovery (Point et al. 2017). Examples of commercial processes for P recovery and the different final P products derived are thoroughly listed and discussed (Melia et al. 2017). Potassium recovery from wastewater has not been substantially considered and is an emerging issue (Batstone et al. 2015). There are also quite number of other promising nutrient recovery technologies that are yet invalidated, such as microbial recovery cell- anaerobic osmotic membrane bioreactor ((MRC)-AnOMBR system (Hou et al. 2017), reactive sorbents (Hermassi et al. 2018) and microalgae (Viruela et al. 2016).

3.2.2 Recovered materials: PHA

Biopolymers are a group of polymers with similar properties to petroleum-based plastics, produced from renewable sources also by different types of bacteria using carbon as a substrate (Raheem et al. 2018). The main advantages of PHAs are the possibility of being completely biodegradable and non-toxic. PHA-storing bacteria are well-known to grow in activated sludge processes of WWTPs that store these polymers as carbon source and energy reserve (Frison et al. 2015). The series of operations needed for microbial production of PHAs are substantially described in the literature (Tamis et al. 2014; Anjum et al. 2016). Ongoing pilot-scale demonstrations in recent years offer fundamental experience to produce PHA from waste materials in enough quantities to inspire value chains and investment within first bio-based value chains. To launch the private and public relationships that will drive the economic and regulatory framework, it is a crucial to verify and explore technology process basis, to validate recovered material flows to marketable renewable resources (Valentino et al. 2017). SMARTech2b stands as the key to enable secondary mainstream energy-efficient resource recovery in Manresa WRRF, Spain. It applies the mainstream SCEPPHAR (Short-cut Enhanced Phosphorus and PHA Recovery) and consists of two sequencing batch reactors (SBRs); one for heterotrophic bacterial growth operated under anaerobic/anoxic/aerobic sequence (HET-SBR), and another SBR for autotrophic nitrifiers growth (AUT-SBR), an interchange vessel and a chemical system for P-recovery as struvite. The integrated system accomplishes enhanced N-removal and P-recovery in municipal WWTP. PHA is recovered from the anaerobic purge of the SBR. SMARTech5 also applies the SCEPPHAR concept in Carbonera WWTP, Italy, which was conceived as a modified version of SCENA where PHA recovery is an economically sustainable option. It accounts of the following subprocesses: (i) cellulosic primary sludge fermentation to enhance the production of VFAs and release nitrogen and phosphorus in soluble forms (i.e. ammonia and phosphate); (ii) solid and liquid separation of the fermentation products and recovery of struvite form the sewage sludge fermentation liquid by the addition of $Mg(OH)_2$ to favour the precipitation; (iii) ammonium conversion to nitrite accomplished in a SBR; (iv) selection of PHA storing biomass in a SBR by the alternation of aerobic feast conditions and followed by anoxic famine conditions for denitritation driven by internally stored PHA as carbon source; (v) PHA accumulation using a fed-batch reactor to maximize the cellular PHA content of the biomass harvested from the selection stage. Within the context of the INCOVER Project, pilot-scale mainstream phototrophic PHA recovery is conducted in

Viladecans, Spain. PHA is produced through photo-bioreactors in which microalgae and cyanobacteria communities grow in a symbiotic relationship, removing pollutants from urban and agricultural wastewaters and accumulating PHA. Produced biomass is then fed into the AD with sewage sludge or other biomass sources as co-substrate for biogas production (incover-project.eu). An innovative biogas upgrading technology is also implemented, based on the symbiosis between microalgae and bacteria and the photosynthetic fixation of CO, which removes CO and HS to produce biomethane of 92%. In El Torno WWTP, Spain, PHA production is produced through two-stage anaerobic-photosynthetic high rate algae pond systems that are consisting of pulse feeding of municipal wastewater pre-treated in an UASB reactor with molasses as COD source. Similarly, after PHA production, the remaining biomass is converted into biogas using thermal pre-treatment and an anaerobic co-digestion process followed by biogas upgrade.

3.2.2 Recovered materials: Cellulose

Municipal wastewater contains high amounts of cellulose fibre (30–50% of the total suspended solids) that is mainly originated from toilet papers (Behera et al. 2018). These cellulose fibres easily enter biological treatment systems of WWTPs if they are not separated during the primary treatment; biodegradation of cellulose is comparatively difficult and depends on many factors (Ruiken et al. 2013; Crutchik et al. 2018). On the other hand, cellulose fibres hold a great potential as a resource which can be recovered from wastewater by sieving (Ruiken et al. 2013). The benefits of cellulose dewatering sludge are: minimization of chemical consumption, lower electricity consumption for aeration, less chance of phosphate release and much lower sludge volume to discharge that reduces sludge handling and management cost. Cellulose harvesting is expected to have added benefits to the WWTP's downstream biological process and provided outside the WWTP for the downstream blending with PHA and processing for final biocomposite production. SMARTech1 comprises an innovative integration of dynamic fine-sieving together with in-situ post-processing that is currently validated in the municipal WWTP of Geestmerambacht, Netherlands. CirTec has developed flow scheme with filter for primary treatment (Salsnes Filter^{TM}) and separating cellulosic fibres to produce a highly-concentrated sludge. The produced cake layer or fine sieved fraction (FSF) harvested from Salsnes Filter^{TM} has a very heterogeneous composition containing mainly cellulosic fibres originating from toilet paper. The result is a market-ready cellulose that has been cleaned, dried and disinfected. Examples of the recovered materials from WWTPs in SMART-Plant are shown in Fig. 1.

4. Technologies to the market: focus on the environmental technology verification and other performance certifications

At EU level, innovative environmental technologies are validated by Environmental Technology Verification (ETV) Program to prove the reliability of the developed claims and help technology purchasers identify innovations that suit their needs. Hence, the best long-term technical, environmental and economic performances are validated by ETV protocol. ETV ensures that the performance claims are as structured and complete in order to present a clear assessment of the technology's potential and value. However, it does not cover the evaluation of the technology's performance against standard or pre-defined criteria. More information can be found at ETV's official website (https://ec.europa.eu/environment/ecoap/etv_en).

In addition to validation of a technology, the functional properties of recovered materials should be determined using specific functional tests to compare recovered products with industrial products. The use of phosphate salts, biochar and pyrolysis materials, is more controlled and regulated compared to other recovered materials. The European Sustainable Phosphorus Platform (ESPP) are implementing many activities for the sustainable management of phosphorus and other nutrients. STRUBIAS - EU Fertilisers Regulation - sets criteria for nutrient recovery rules within EU Fertilising Products Regulation. At national level, authorisations of struvite/recovered phosphates as fertilisers together with phosphorus recycling legislations are in force in some EU countries. The main challenge of these organic-based fertilizers is to ensure that their application is not resulting in an accumulation of different organic non-biogenic and inorganic compounds (e.g., toxic metals and non-metals) (Hermassi et al. 2018). Strong debates continue regarding the social awareness of consumers and framework regularities about food security (3rd European Nutrient Event, 2018).

Inconsistency and high-variability of available sources for recovered PHA quality in routine production is still a hidden gem (Valentino et al. 2017). For instance, the extracted PHA from municipal secondary wastewater was examined using ^{13}C NMR spectroscopy (Kumar et al. 2018)**.** Size exclusion chromatography (SEC) and differential scanning calorimetry (SDC) were also used for the characterization of the recovered PHA (molecular number, molecular weight, glass transition temperature etc.) (Frison et al. 2015). However, consistent quality of recovered PHA derived from wastewater as feedstock has not been proven or refuted presenting a big challenge in scaled-up implementations (Valentino et al. 2017).

5. Valorisation of recovered materials to consumer/industrial products

Sustainability assessment of the recovered materials from wastewater was conducted (Zijp et al. 2017) with respect to 6 different categories as follows: economic welfare, resource depletion, environmental and biological quality, technical welfare, human health and social welfare. It was concluded that PHA and struvite seemed economically feasible in terms of production costs and market values. However, PHA needs urgent and further investigations as it exhibits some critical barriers, which have to do with the possible emissions of toxic compounds during the production stage and concerns regarding the perception of the market on the food security. Similarly, struvite utilization also depends on location-specific aspects and legislations and needs further assessment. Cellulose recovery and application, on the other hand, seems less feasible due to the costs of extra hygiene step when used in the paper and carton industry. This step is not required in construction applications which makes cellulose recovery more beneficial for all resource themes. In a recent study, better value was derived from valorising CPS to VFAs and struvite from the fermentation liquid, then CH_4 was further recovered after AD of remaining fermentation solids (Crutchik et al. 2018). The authors made a simple comparison by assuming CH_4 market price of 0.11 €/m^3, the best valorisation of CH_4 from CPS could be up to 0.46 €/capita·year. Acetate and propionate price could be as high as 0.45 and 1.01 €/kg, respectively, meanwhile struvite could be sold up to 0.76 €/kg. Therefore, the VFAs and struvite route before biomethanization have the potential to increase the market value potential of CPS up to 1.55-1.95 €/capita·year (Crutchik et al. 2018). Overall, potential end-use of the recovered materials with respect to market requirements highly influence its role within circular economy. Some of the potential end-uses of the recovered materials from WWTPs are discussed with existing market values and possible valorisation alternatives.

The different market possibilities and the discussion of the advantages and disadvantages for the recovered materials commercialization opportunities are summarized in Table 5.

5.1. Market possibilities for recovered materials: Nutrients

Adding nutrient-loaded sorbents enhances the soil quality in terms of agricultural yield and nutritional quality. However, socioeconomic conditions highly influence whether such materials can be applicable in commercial agriculture. The key factors that influence the application of post-sorbent fertilizers are the availability of feedstock, the technology to manufacture fertilizers, and the investment costs and capacity. (Hermassi et al. 2018). In addition, soil measurements together with plant bioavailability indices can help to determine fertilizer performance (Peng et al. 2018). Effects of struvite as fertilizer on various plants can be found (Kataki et al. 2016).

The market value of struvite varies from 188 to 763 €/t struvite in the recent years (Molinos-Senante et al. 2011; Desmidt et al. 2015). Although economic feasibility of struvite recovery is limited by high operational costs, it was also determined that when the struvite sale price is assumed as 560 €/ton, the net profit of445.62 €/day was obtained for a full-scale fertilizer production industry with a 500 m^3/day capacity. (Yetilmezsoy et al. 2017). The European Commission’s draft “market study” assesses the possible sources of raw materials for nutrient recycling, STRUBIAS technologies and economic aspects. High quality of these struvite-based products enables them to be used as effective slow-release fertilizers for agriculture practices. Furthermore, P recovery also aids to cease eutrophication in aquatic environments. In this regard, if economic aspects for P recovery are not satisfactory, environmental benefits and government regulations could be the driving force (Peng et al. 2018). During the market development strategy for struvite, focus should be based on a holistic approach considering pricing, demand, purity, size, storage, transportation and distribution with respect to the existing regulatory framework of contaminants and eco-toxicity (Desmidt et al. 2015; Kataki et al. 2016).

5.2. Market possibilities for recovered materials: Biopolymers

Biopolymers must compete with petroleum-based polymers, which are available in high amounts at relatively low prices. Biogas could be also considered the main competitor for biopolymer production in WWTPs since organic carbon from waste material will not be diverted for the production of biopolymers when the production of biogas is more convenient (Kleerebezem et al. 2015). Thus, the market potential of bioplastics seems limited so far (Van Der Hoek et al. 2016). However, (EEA report No 8/2018) reported that the global production of plastics is estimated to account for about 7 % of the world's fossil fuel consumption. The proportion of bioplastics is still low, currently below 1 %. However, the worldwide biopolymer production capacity is forecast to increase from 6.6 million tonnes in 2016 to 8.5 million tonnes in 2021.

Production of biopolymers from waste feedstock seems advantageous and economical depending on the market requirements. It has multiple applications especially in material and packaging industries and utilisation of waste feedstock as substrate makes a great contribution to waste management and reduces environmental pollution. For instance, these waste materials are proved to be efficient substrates producing significant amounts of PHA or extracellular polymeric substances (EPS) that can help to reduce the production cost by eliminating the usage of pure carbon sources. Research is still on-going for the lower-cost production of PHAs by utilization of such low cost wastes and using wild and mutant strains of microorganisms (Anjum et al. 2016). Optimization of the processing techniques can pave the way to take PHA formation from waste materials to industrial level and then into the market (Pakalapati et al. 2018). At the moment, the bottleneck of the process seems to be the extraction of PHA from the biomass which requires thermal and/or chemical processes which are usually expensive.

5.2.1 Market possibilities for recovered materials: PHA

PHA has gained greater attraction in the recent years due to their many advantages such as biodegradability, biocompatibility, controllable thermal and mechanical properties as well as molecular weight diversity, which allow them to be used as bioimplant materials for medical and therapeutic applications (Zhang et al. 2018). Although the utilization of waste materials for the synthesis of high-class materials such as PHAs has led to cost reduction as previously mentioned, the final products cannot be used in medical applications where high purity products with non-toxic nature are of utmost considerations (Raza et al. 2018). PHAs recovered from waste materials can contain viral, plasmid, bacterial or genetic contaminations that hinder their potential usage for medical applications. Impurities in PHA regarding proteins, lipids, endotoxins, antifoam agents, DNA and hypochlorite have been previously reported (Koller et al. 2013b, a). Such impurities require specific post recovery washing procedures that eventually cause a major increase in product cost (Raza et al. 2018).

In this regard, the majority of recovered PHA applications take place in a wide range of products including paper coatings, bags, containers, food packaging materials, bottles, cup etc. (Muhammadi et al. 2015). For instance, water-resistant layer for paper, film or cardboard can be produced out of the latex of PHAs (Anderson and Dawes 1990; Bourbonnais and Marchessault 2010). PHAs can also be used to replace petrochemical polymers in toner and developer compositions as well as ion-conducting polymers (Muhammadi et al. 2015).

Industrial PHAs and their applications were discussed by Anjum and colleagues (Anjum et al. 2016). Among these materials and their applications, recovered PHA can find its own place in such practices: Biopol (co-polymer of poly (3-hydroxybutyrate-co-3-hydroxyvalerate)), currently produced by Metabolix (Cambridge,MA, USA), can be used in packaging materials, shampoo bottles, disposable razors, disposable cups, disposable knives and forks. Nodax (PHA copolymer family consisting of 3-hydroxybutyrate) (P&G Chemicals, USA/Japan) is available as foams, fibres or nonwovens, films and latex among others. Biogreen (Mitsubishi Gas Chemicals) developed the production of P (3HB) from methanol, and markets it under the trade name Biogreen. Furthermore, PHAs can be used to make foils and diaphragms, pressure sensors for keyboards, stretch and acceleration measuring instruments, material testing, shockwave sensors, lighters, gas lighters; acoustics, and for ultrasonic therapy and atomization of liquids (Anjum et al. 2016). A high performance of PHA biopolymer, Minerv-PHA (Minerv, Italy), takes the place of highly pollutant materials such as PET, PP, PE, HDPE and LDPE. The most known commercially-available PHA products can be found elsewhere (Bugnicourt et al. 2014).

Other than being used mainly as environmentally friendly plastics for packaging purposes, PHAs are considered as a source for the synthesis of chiral compounds which highlights them as raw materials for the production of paints (Reddy et al. 2003; Muhammadi et al. 2015). Furthermore, PHA can be hydrolysed chemically, and the monomers can then be converted into molecules such as 2-alkenoic acids, ß-hydroxy acids, ß-hydroxyalkanols, ß-hydroxyacid esters, ß-acyllactones, ß-amino acids, which hold great potential as biodegradable solvents (Madison and Huisman 1999; Muhammadi et al. 2015). Other important, industrial applications of PHAs are printing and photography, art-smart gels, heat-sensitive-adhesives and also fishing equipment (Pakalapati et al. 2018).

Blending PHAs, in particular polyhydroxybutyrate (PHB), with other polymers, or with plasticizers, creates opportunities to enhance their properties by decreasing the processing temperature and lowering the brittleness of PHAs based plastics. So far many blends containing PHB/PHAs have been investigated and several types of plasticizers have been proposed (Bugnicourt et al. 2014).

In addition, nanocomposites of PHA are also reported (Anjum et al. 2016). For example, the preparation of biodegradable nanocomposites using NFC and poly(3-hydroxybutyrate-co-3-hydroxyvalerate, PHBV) as the polymer matrix has been investigated (Srithep et al. 2013). This can be a good alternative to valorise two types of recovered materials from WWTPs in one application.

PHA yield on carbon source, its productivity and downstream costs determine their introduction into the global market (Możejko-Ciesielska and Kiewisz 2016). The selected end-use of PHA often determines the market specifications and requirements.

The current cost of PHAs production and recovery with aqueous two-phase extraction method is stated as 5.77 USD/kg. However, utilizing a cheaper carbon source such as sludge has the potential to reduce the final PHA production price significantly (Leong et al. 2017). Hence, the theoretical price of PHAs produced in fed-batch mode using waste materials could reach up to 3.51 €/kg. Yet, they are still not cost-efficient when compared to their synthetic alternatives such as polypropylene and polyethylene, which cost 1.47 and 1.15 €/kg, respectively (Możejko-Ciesielska and Kiewisz 2016). The current PHA price ranges between 2.2-5.0 €/kg, which depends on monomer composition and is usually higher for the copolymers. In spite of having several environmental advantages, the PHA prices are still not commercially-competitive with conventional petroleum-based polymers, which typically cost less than 1.0 €/kg (Valentino et al. 2017).

5.2.2 Market possibilities for recovered materials: EPS

EPS are biopolymers that are considered eco-friendly, cost effective and sustainable alternatives to substitute the existing chemical flocculants. Potential environmental applications of EPS can be listed as follows as summarized from More et al., 2014): Water treatment (Wang et al. 2012), wastewater treatment (Li et al. 2013), colour removal from wastewater (Liu et al. 2009), sludge dewatering (Yang et al. 2012), metal removal or recovery (Mikutta et al. 2012), removal of toxic organic compounds (Zhang et al. 2011), landfill leachate treatment (Zouboulis et al. 2004) and soil remediation and reclamation (Chandran and Das 2011). Existing literature is limited to lab-scale applications and further research is still needed to be scaled up to field applications since EPS can be used as a cost-effective treatment alternative. The cost of the EPS extraction and purification can be the limiting factor in the field application considered of various sectors with chemistry, structure and properties of interest (More et al. 2014).

5.3. Market possibilities for recovered materials: Cellulose

Classification of cellulosic materials as well as current and emerging markets for cellulose-based products have been thoroughly discussed (Keijsers et al. 2013). Accordingly, cellulose markets were classified into 9 categories: Textile, non-woven, wood and timber, pulp/paper and board, cellulose dissolving pulp, cellulosic films, building materials, cellulosic fibre composites and green chemicals. The selected end-use of a certain lignocellulosic raw material often specifies the market requirements. Hence, the end-use of cellulose determines the market prices and volumes, which are directly linked to the cellulose quality and defined over physical properties, chemical composition, unwanted components, prior treatments of raw material, and physical, chemical, biological stability of the cellulose. For instance, end-uses for cellulose such as pulp, paper and board are pointed on brightness, tensile and tear, freeness, write-ability; the price range is between 450-650 raw material price €/ton. Polymeric cellulose will eventually have higher chemical purity requirements. Meanwhile, market requirement of building materials for extracted cellulose is based on its strength, moisture absorbency and fire retardancy. Details of market volume and market price of purified celluloses can be found in the literature (Keijsers et al. 2013).

Considering its nature and high energy content, fine sieved fraction (FSF) has started to gain attraction in countries such as the Netherlands (Ghasimi et al. 2016). The recovered cellulose can be used either as raw material to make paper products, adhesion binders for asphalts (Crutchik et al. 2018) or as the fibrous reinforcement material in bricks (Kim et al. 2017) when properly separated and refined. For instance, cellulosic material recovered from screenings were used as an ingredient in the production of asphalt to create a bike path near Beemster WWTP, the Netherlands (Selster A.S., 2018). Similarly, Makron (Finland) uses recycled cellulose fibre additives for asphalt.

The use of natural fibres as the adsorbent is another emerging trend in environmental engineering applications including environmental remediation and water filtration membranes as the fibres are abundant, readily available and are more environmentally friendly compared to carbon based materials (Carpenter et al. 2015). They are used as adsorbents in wastewater treatment (i.e. in the form of membrane) and for the removal of adsorbates such as oil, dyes, heavy metals and ionic compounds (Rahman et al. 2018). As the production of effective adsorbents at low cost and low energy consumption is placed at the centre of many researches, the properties and possible modifications of recovered cellulose need to be thoroughly investigated and understood.

Furthermore, market projections of cellulose nanomaterial-enabled products are estimated (Cowie et al. 2014) and recent developments in production of cellulose nanofibrils (CNF) were discussed (Nechyporchuk et al. 2016). Fluorescent cellulose bio-based plastics were successfully fabricated based on the strong hydrogen bonding interaction between cellulose chains and conjugated dye molecules, and further suggested as a good candidate for making anti-counterfeiting banknotes (Wang et al. 2016). In another study, the transparent and flexible cellulose-based nanocomposite papers were fabricated to be used as solar cell substrates (Cheng et al. 2018). However, smooth surface was proposed to be maintained on the cellulosic material to avoid problems during the coating process. The use of cellulose nanocrystals for thermal insulation can be another option to value recovered cellulose from WWTPs (Septevani et al. 2017). CNF can be combined with clay for the preparation of nanopaper to obtain unique brick-and mortar structure (Carosio et al. 2016).

Cellulose can be efficiently used to produce valuable chemicals or biofuels, such as VFAs (Guo et al. 2015), poly lactic acid (Graupner et al. 2009; Jamshidian et al. 2010) and bioethanol (Zabed et al. 2017). However, it should be noted that the use of cellulose for biogas and bioenergy production are positioned at the bottom of the biomass value pyramid (Gavrilescu 2014).

The possibility to use the separated materials to safely produce toilet paper was also suggested as a real cradle to-cradle application, but difficulties in relation to social acceptance were also highlighted (Ruiken et al. 2013). In all conditions and possible applications, extraction and purification methods of cellulose must be thoroughly studied to assess its feasibility to meet the criteria of end-use markets.

Table 5. Market possibilities, quality indicators and market price range for recovered struvite, PHA and cellulose.

Product	Market possibilities	Quality indicators	Price range (€/t)	Reference
Struvite	• Fertilizer	• Solubility, purity, plant bioavailability, metal content, crystal size	• 188-763	(Molinos-Senante et al. 2011; Peng et al. 2018)
PHA	• Paper (coating) • Packaging (foils) • Electronics (headphones, keyboards) • Printing and photography • Others	• Purity, toxicity, chemical constituents, blending	• 2.2-5.0 €/kg	(Anjum et al. 2016; Valentino et al. 2017)
Cellulose	• Textiles	• Purity/colour/fibre length/distribution/lustre/ softness/hygienic	• 1200-1900	(Keijsers et al. 2013)
	• Non-woven	• Purity/fibre length/ distribution/ absorbency	• 200-400	
	• Wood, timber	• Density/strength and modulus/durability/hardness/colour	• 450-600 €/m^3	
	• Pulp, paper and board	• Brightness, tensile and tear, freeness, writability	• 450-650	
	• Cellulose dissolving pulp	• α Cellulose %, polymerisation degree	• 1600-2000	
	• Cellulosic films	• α Cellulose %, polymerisation degree	• 3000-3500	
	• Building materials	• Strength, moisture absorbency, fire retardancy	• -	
	• Cellulosic fibre composites	• Compatibility	• 200-400	
	• Green chemicals	• Glucose yield/extractability	• 50-100	

5 Barriers to resource recovery and reuse and solutions to overcome

Actually, notwithstanding the important research activities and the developed technologies for resources recovery from the real WWTPs, many bottlenecks for the market uptake and for their application could be identified.

In fact, the law for water reuse, actually, regulates only the irrigation purpose. None specific indications and legislations were clearly promoted for fertigation objective as highlighted even by EU Innovation Deal on sustainable wastewater treatment combining anaerobic membrane technology and water reuse. Many lacks have been identified both in the legal definition of the term discharge and for quality standards provisions adopted for wastewater effluents to be used for agriculture. Moreover, recognition of the economic and environmental benefits of water reuse within reclaimed water pricing have to be implemented.

For phosphorous and ammonia salts, more detailed studies and programs have been developed at European level to overcome regulatory barriers. Not similar evidences have been identified for PHA and cellulose potential recovery.

Moreover, the quality, the purity and the characteristics of the recovered resources change on the basis of the implemented process in the WWTPs. From the other hand, the different market sectors request inlet materials with diverse standards on the basis of the final productive application. For this reason the certification of the technologies, which also has to include the main properties of the recovered products, seems necessary to couple the recovery processes to the industrial sectors.

In this direction, the European criteria of “End-of-waste” could be identified as possible legislative solution to support the resources recovery application in the WWTPs. In fact, this approach (Waste Framework Directive 2008/98/EC) specifies when certain waste ceases to be waste and obtains a status of a product or a secondary raw material. The obtainment of the end of waste status has to be supported by several conditions: 1- the substance or object is commonly used for specific purposes; 2- there is an existing market or demand for the substance or object; 3- the use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products); 4- the use will not lead to overall adverse environmental or human health impacts. Starting from this point, specific regulations, centred on the end of waste concept, could be implemented to support the regulatory framework of the resources recovery. This approach can justify and encourage the technological investments in the WWTPs to economically address and support the resources recovery and to promote the circular economy in the water sector (Guest, et al., 2009).

Finally, public perception and social acceptance are insufficiently developed for all the described materials. Therefore, specific formative and public dissemination activities have to be strongly supported.

6 Conclusions

This paper has provided a commentary on recent advances in energy-efficient resource recovery approaches in WWTPs. Anaerobic processes stand as the “gold mine” in wastewater mining strategy while AnMBRs are the “gold diggers”. While the biorefinery concept has been widely recognized, lab-scale studies are gradually evolving into validated pilot/full scale implementations. Onsite energy recovery is still getting most attention. However, recently-developed and validated processes, such as SCENA and SCEPPHAR, derive more value to VFAs, while achieving satisfactory nutrients and PHA recovery, respectively. Together with nutrients and PHA, cellulose is another value-added material to be recovered in WWTPs. Among all the energy and material recovery methods, some are consistently considered to be beneficial to improve sustainability, and some of them still need further research to achieve desired feasibility. Struvite has a comparatively large market, also brings strong debates on food security that needs to be addressed in the near future. Valorisation of PHA and cellulose, by the way, should not be overlooked since there are huge market alternatives. Therefore, there is a need to develop the regulatory framework for resource recovery and carry out socioeconomic assessments considering the market potential and specific requirements.

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Figure captions

Fig. 1. Examples of the recovered products in the context of SMART-Plant Project **(a)** Recovered PHA from SMARTech2b in Manresa WWTP, Spain **(b)** Recovered struvite from SMARTech5 in Carbonera WWTP, Italy **(c)** Recovered cellulosic sludge from Geestmerambacht WWTP, Netherlands