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## WATER IMPACT STATEMENT

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Models have been successfully used in operation, design and control of wastewater treatment processes. With the increasing attention to resource recovery from wastewater, this perspective paper discusses to which extent the new unit processes applied for resource recovery can be modelled with conventional activated sludge models and to which extend additional modelling challenges are faced.



# Environmental Science: Water Research & Technology

## PERSPECTIVES

### Resource recovery and wastewater treatment modelling

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Traditional wastewater treatment plants (WWTPs) are increasingly regarded as water resource recovery facilities (WRRFs), reflecting the value of water, nutrients, energy and other resources, besides ensuring the required effluent quality. Resource recovery techniques involve biochemical, physical and physico-chemical processes, and even previously unexploited biological conversions. Biopolymers and bioplastics production also reveal the remarkable potential present in our microbial cultures. Models have demonstrated their usefulness to optimize WWTP operation to achieve better effluent quality at lower costs; they also constitute a useful tool to support the transition of WWTPs into WRRFs that maximize the valorization of products recovered from the wastewater. In this paper, it is discussed to which extent the new techniques and unit processes applied for resource recovery could be modelled with conventional activated sludge models (ASMs) and which additional modelling challenges are faced while providing recommendations of potential approaches to address current modelling research gaps.

## 1 INTRODUCTION

The goals of wastewater treatment have evolved over the years. It originated from the needs of sanitation and moved towards protecting the environment. The concept of circular economy has gained traction in the last few decades as a potential key to solving the rising scarcity of resources due to urbanization and population growth. Nonetheless, the resource recovery approach is not new.<sup>1</sup> Actually in Prague, Amsterdam and several other European countries, the wastewater was first used as a resource for phosphate and nitrogen recovery before wastewater treatment plants were built.<sup>2</sup> Wastewater treatment came after resource recovery, and now the past is being revisited.

The type of resource recovery practiced nowadays is primarily aimed at improving the general operation of the treatment plant. An example is sludge digestion to reduce the amount of sludge in the first place and having biogas production as an on-the-side benefit. A similar example is struvite recovery, which is performed primarily to reduce the maintenance cost associated with struvite precipitation in the plant, even though utilities often specify that it is for phosphate recovery.

Activated sludge models (ASMs)<sup>3</sup> have successfully formed the industrial standard for wastewater treatment process modelling, even though they are a simplification of reality and do not encompass all scientific knowledge. Aside from teaching and research purpose, the aim of the ASMs development was to obtain a simple model with a minimum number of parameters, which operators and designers could work with and could use to analyse wastewater treatment plants.<sup>4</sup> Indeed, the ASMs describe oxygen dynamics (through the COD balance) and thus aeration demands, sludge production and effluent quality in terms of COD, nitrogen and phosphorus (i.e. ASM2/2d/3). The aeration requirements, sludge production and the need for recycle pump capacity are actually an outcome of ASM1. Prediction of biogas production could also be included. Unit processes such as crystallizer and nanofiltration units are not covered by the ASMs and would need dedicated models to describe struvite and water recovery, respectively. In all cases, resource recovery models need to well describe product specifications, similar to effluent characteristics for wastewater treatment models.

Resource recovery units will often be operated in relatively stable conditions and not with the same dynamics as in the main water line of the treatment plant. Thus, there is less need for dynamic models and stoichiometric models may be adequate enough to describe most recovery processes. However, dynamic modelling is still useful for optimization, especially when taking into account the interaction of the recovery process with the rest of the wastewater treatment plant unit processes.

There may be a need to make dedicated models for dedicated processes, for instance, model for design of a struvite reactor

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for struvite recovery. It may not be useful to make one model similar to ASM1 suitable for all resource recovery options. What is needed is that these resource recovery models use the same state variables such that they can be integrated for a specific site. For plant-wide simulation studies, these dedicated models could be coupled with other existing models by constructing model interfaces as detailed by Volcke *et al.*<sup>5</sup>

Wastewater treatment plants are often considered in a larger context, including sewers supplying the wastewater, water bodies to which the treated effluent is discharged and maybe even water reclamation facilities. When considering resource recovery, looking beyond the fence of a wastewater treatment plant is even more needed because the amount of resources a single plant can deliver may be too small to be recognized as a real resource factory, for instance, in the case of bioplastics.<sup>6</sup> Wastewater handling needs to be integrated into the whole urban water system, considering the interactions of the individual pieces, and this holds even more true when resource recovery comes into play. Integration allows for a holistic approach to management and possible cost-effective solutions.<sup>7</sup> There should be more focus on models which include the economy and also life cycle analysis in the context of product formation and product.<sup>8</sup>

This contribution deals with modelling needs associated with the reconfiguration of wastewater treatment plants (WWTPs) into water resource recovery facilities (WRRFs). The focus lies on recoverable resources that are being exploited at a large scale or at least have the potential to be so, tackling a number of questions. Are the activated sludge models (ASMs) still state of the art? Are they still relevant? Or should a completely different set of models be used? And which modelling needs does the integration of wastewater treatment in a larger context bring about?

## 2 RECOVERABLE RESOURCES

### 2.1 Energy

#### Biogas – carbon redirection

In the context of resource recovery, organics in the wastewater can be considered as reservoirs of energy rather than pollution. Energy generation is included and implemented in the ASMs through consideration of organics measured as chemical oxygen demand (COD). Techniques such as enhanced primary treatment and high-rate activated sludge systems have often been used to increase the amount of organics that are sent to the anaerobic digester, wherein these organics are converted to biogas.<sup>9</sup> For anaerobic digestion, the important thing is to know how much biodegradable particulate COD and active biomass fraction gets out of the activated sludge because those are the

fractions which are converted to methane. Thus, there is no need for further complexity for the anaerobic digestion models<sup>10,11</sup> with regards to energy recovery. Anaerobic co-digestion is also being utilised to maximize biogas production (as modelled by Zaher *et al.*<sup>12</sup>), even though problems due to pH changes can be encountered when food wastes and other types of substrates are added into the digester. It should be pointed out, however, that importing food waste into the wastewater treatment plant does not equate to recovery because it is not actually improving the energy recovery efficiency from wastewater itself but increases the energy production by introducing an external energy source (i.e. food waste). This is an action that can be done by any water utility, but it is not generating additional energy from the wastewater as such.

A-stage systems, such as high-rate activated sludge, are nowadays being explored for carbon redirection.<sup>13</sup> There is a high variability in the efficiency of the conversion and solid-liquid separation processes among the different A-stage plants. ASMs can do a very good job describing high-rate systems as demonstrated by Smitshuijzen *et al.*<sup>14</sup> The most important aspect is to recognize that a part of the biodegradable soluble COD fraction is colloidal material which will not be converted by bacteria in an A-stage but would then be removed in the settler. In this case, dedicated wastewater characterization is essential. Nogaj *et al.*<sup>15</sup> developed a modified ASM1 considering dual soluble substrate (i.e. fast and slow) and additional processes related to these dual substrate, extracellular polymeric substances (EPS), storage products and colloidal substrate. Apart from proper wastewater characterization, additional parameter estimation and validation should be performed due to new included model state variables, parameters and processes. A crucial part in an A-stage system is not the biological part but rather the flocculation part. The formed flocs are extremely weak such that the way the inlet system to the A-stage clarifier is constructed will strongly influence how and how much suspended solids will end up in the A-stage clarifier effluent.<sup>16</sup> Describing the inlet mixing phenomena as done for secondary settlers<sup>17</sup> could prove useful. This aspect of floc formation should be examined first before directing all efforts to make an improved ASM for modelling A-stage systems.

#### Heat recovery

Arising from hot water use (e.g. for bathing, cleaning), wastewater originating from households retains part of its thermal energy as it flows from the domestic source to the centralized WWTP. The recovery of this thermal energy can be done at the source (i.e. households or buildings), along the sewer line, or at the WWTP.<sup>18</sup> The larger quantity of recoverable thermal energy due to larger volumetric flows is the main reason why heat recovery at large-scale centralized WWTPs attracts more attention. Heat can be recovered from the effluent, digester sludge or filtrate through heat pumps

and/or heat exchangers. Heat recovery from the influent (or in the sewer) is also possible, when done in a controlled way, to avoid negative effects on treatment process efficiency.<sup>19</sup> The thermal energy produced by such heat pumps with wastewater as heat source are on average 3.5 times higher than the electrical energy required to power them.<sup>20</sup> The recovered energy can then be used for cooling/heating the office buildings in the WWTP and for process heating (e.g. sludge drying) and thus, can directly offset the electricity costs related to the heating demands of a WWTP, and for larger-scale heat recoveries, can even be distributed through district heating systems.<sup>21,22</sup> Still, the most commonly applied approach for heat recovery at a WWTP is utilizing the calorific value of digester biogas by burning it in a boiler (only heat production) or in a combined heat and power generation unit. The recovered heat is then typically used to heat the digester.

Investigating the viability of heat recovery from a WWTP evidently requires setting-up heat balances considering the heat that is produced during biochemical reactions, that is lost/gained through the air/liquid interface, that is associated with the influent and effluent flows, and that is transmitted from mechanical actuators, among others. This allows prediction of temperature in the context of wastewater treatment and has already been sufficiently demonstrated in several studies.<sup>23,24</sup> Corbala-Robles *et al.*<sup>25</sup> extended previous temperature prediction models in biological reactors, in particular considering the effect of a foam layer, which significantly affects heat loss through the surface as a major factor influencing reactor temperature. A systematic description and calculation of heat fluxes in biochemical reactors within a plant-wide model, coupling the ASM reactions and multi-phase biochemical transformations with heat balances, has also already been illustrated, e.g. by Fernández-Arévalo *et al.*<sup>26</sup> The focus should now turn to detailed cost analysis for specific case studies to determine the economic viability of heat recovery, which is dependent on current energy costs and the balance between heat production and heat requirements.<sup>27</sup> Not only should it be possible to use the amount of heat recovered on-site, it should also be available at the time there is a demand, since heat transport and/or storage would pose additional challenges. Aquifer thermal energy storage systems, for example, can be used to achieve on-site heat storage and recovery.<sup>28</sup> The heat supply and demand, influenced by climate and local conditions, should thus be analysed to determine the technical and economic feasibility of a thermal energy generation unit.

## 2.2 Nutrients

### Phosphate

One of the most common chemical compounds recovered from wastewater is struvite. It should be noted that for the most part, recovering struvite is not the main goal of water utilities but rather reducing the operational issues due to struvite scale formation.<sup>29</sup> Typically, the recovered struvite has not yet reached more than 25% of the influent phosphate load.<sup>30</sup> Processes other than struvite recovery should be considered if one is really interested in phosphate recovery. Consideration of phosphate in the wastewater and its recovery involves chemistry and microbiology that are more complex than what is typically included in the ASMs.<sup>31,32</sup> Phosphate chemistry can be easily included by coupling ASMs with geochemical modelling software such as PHREEQC<sup>33-35</sup> or with aqueous phase chemistry modules.<sup>36-38</sup>

In view of phosphate recovery, it is essential to include relevant metals in the influent, especially iron,<sup>31,39,40</sup> through the use of aqueous phase chemistry and precipitation models as already demonstrated by Hauduc *et al.*,<sup>31</sup> Solon *et al.*<sup>41</sup> and Vaneeckhaute *et al.*<sup>35</sup> It is crucial to remark that, independent from whether this is done by coupling the biochemical models with an external geochemical modelling software or with self-coded aqueous phase chemistry and precipitation models, expert knowledge is of paramount importance to ensure that all relevant chemical components and species are accounted for. In addition, regarding the interest on vivianite (Fe(II) crystals), models for iron oxidation and reduction still need to be validated. These phenomena are kinetically limited and depend on the presence of other electron acceptors and donors. Iron is quite often neglected although sewer systems which have anaerobic groundwater intrusion result in significant iron in the influent of the WWTP. There could also be other sources of iron in the sewer systems. In fact, quite a number of bio-P treatment plants in the Netherlands may achieve 20-50% chemical phosphate removal, as a result of the amount of iron in the influent wastewater.<sup>42</sup> If the iron fraction in the influent is not taken into account, the bio-P model alone is not suitable. In addition to the iron that is already included in the influent, some of the externally added iron will precipitate with phosphate as vivianite. Vivianite may not be directly useful in agricultural applications but is nevertheless useful for other kinds of industrial processes<sup>43</sup> and is an approach to further increase phosphate recovery.

The calibration of hydrolysis parameters for different organic phosphorus fractions during anaerobic digestion also needs more attention. This will lead to better prediction of the quantity of recoverable phosphorus in the digestate. However, the main challenges in recovering phosphorus from the sewage sludge through the crystallization process (e.g. as struvite, vivianite) is related to the economic feasibility of the process, quality of the product and technical complexity of the process.<sup>44</sup> Complex chemical precipitation models have already been developed, their effect on effluent quality of P recovery units





Extensive life cycle and economic analyses are necessary to determine the practicability of incorporating nitrogen recovery processes in WWTPs since there is no current compelling reason to recover such a renewable resource, aside from the foreseen increasing energy cost associated with the fertilizer production using the Haber-Bosch process.

### Sulfate/Sulfur

Sulfate reduction, autotrophic denitrification and nitrification (SANI) process was developed in Hongkong and applied in coastal areas of China to reclaim saline water without any excessive sludge discharge. ASM-based models have been developed to describe this process.<sup>72</sup> Sulfate is also important if phosphate chemistry is to be considered. Fe-P-S interactions are significant in many redox and bio-precipitation processes.<sup>73</sup> Aerobic sulfur transformations and subsequent interactions with the phosphorus and iron cycles for sewer systems has been described by Gutierrez *et al.*<sup>74</sup> Similar processes has been added to ASMs (and ASM-type models) in order to describe the sulfur transformations in activated sludge systems and its interactions with the phosphorus and iron cycles.<sup>41,75</sup> Fuel gases, such as biogas obtained through anaerobic digestion, may contain significant amounts of sulfur depending on the type of influent wastewater. Biogas desulfurization is often performed and elemental sulfur, S<sup>0</sup>, can be recovered through crystallization and centrifugation of the flue-gas wastewater. For this, dedicated models may be developed to describe the recovery process.

### 2.3 Cellulose fibres

A rather often overlooked resource is fibres. In the wastewater treatment plant influent, 25-30% of the COD and about 40% of suspended solids is attributed to cellulose fibres (i.e. toilet papers).<sup>76</sup> There are more than 300 references in wastewater characterization, however, there is almost no literature on cellulose fibres and a good measurement for cellulose in wastewater or activated sludge is still missing,<sup>76</sup> which is peculiar for such a considerable fraction of the influent COD. Cellulose fibres are easy to remove and recover using only mechanical treatment such as sieves. Initially used as biomass fuel for power plants, recovered cellulose fibres are also being investigated as raw material for paper products, bioplastics<sup>77</sup> and road and building material. It was mentioned in a paper by Nowak *et al.*<sup>78</sup> that there is a very slowly degradable COD fraction in the wastewater. It is probable that this observation was due to cellulose. In line with this and from the point of view of the ASMs, cellulose could simply be modelled by adding a very slowly biodegradable fraction in the ASM.<sup>79</sup> Recent modelling studies pointed out the specificities of the slow hydrolysis kinetics of cellulosic solids.<sup>80,81</sup> Contrary to conventional hydrolysis in ASM, considering the specific hydrolytical active biomass for such material is crucial. Another possibility is to model it as non-biodegradable in high-loaded systems

and biodegradable in low-loaded systems.<sup>82</sup> Economic assessment, energy evaluation and the effect on the overall plant efficiency of integrating cellulose fibre recovery within a WWTP should be studied, taking into account whether it is recovered for energy production or into another product form.

### 2.4 Bioplastics

Bioplastics, such as polyhydroxyalkanoates (PHAs), are produced from renewable biomass resource, making it a better alternative for current petroleum-based plastics commonly in use.<sup>83,84</sup> There are microorganisms found in soil, sewage and marine environments that can synthesize and accumulate PHAs. The main limitation for large scale PHA production is the high cost which is brought about when using pure cultures.<sup>85-87</sup> A promising option, therefore, is the use of mixed cultures. However, there are still investigations on how to improve the yields from such mixed cultures<sup>73</sup> as it has been investigated that activated sludge can accumulate PHA up to 20-60% of the sludge dry weight,<sup>87</sup> compared to pure cultures in which almost 90% can be achieved.<sup>88</sup> PHA from mixed cultures of biomass found abundantly in full-scale municipal wastewater treatment plants is being studied in the PHARIO project in the Netherlands.<sup>89</sup> However, no direct correlation between PHA accumulation potential and storage rate has yet been found in their tests. In principle, PHA accumulation can be modelled by ASM3 as demonstrated by Hanada *et al.*<sup>90</sup> and Guisasola *et al.*,<sup>91</sup> with minor modifications to the kinetic parameters. Even more important to consider than the biokinetic modelling is the assessment of the technological, economic and environmental aspects for bioplastic production technologies, as done by Fernández-Dacosta *et al.*<sup>92</sup> This multi-aspect evaluation can aid in establishing value chains for PHA production for the scale-up of existing technologies.

### 2.5 Extracellular polymers

A mere 10-50% of the total organic carbon in a biofilm are cell biomass, whereas the rest can be found in the biofilm matrix.<sup>93,94</sup> This matrix, called extracellular polymeric substances (EPS), is an aggregation of different types of biopolymers produced by microorganisms which are responsible for the structural and functional integrity of biofilms.<sup>95</sup> Although there have been many studies of EPS characterization,<sup>96</sup> identifying their detailed composition is difficult due to the complexity of the mixture.<sup>97,98</sup> Moreover, their compositions vary and is determined by the origin of the biofilm and by the extraction method used preceding their identification.<sup>99</sup> EPS are a potential resource of polyelectrolytes. They can be applied for soil remediation<sup>100</sup> as an alternative to surfactants in order to improve the water-holding capacity of soil, they can be utilized as a material to make



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nanocomposite materials<sup>101</sup> and they can also be used for metal recovery from wastewater through biosorption.<sup>102,103</sup> Aerobic granular sludge contains a high amount (20-30%) of EPS that have alginate-like properties,<sup>104</sup> which could replace alginate applications. A first extraction facility is currently constructed in the Netherlands.<sup>105</sup> Existing ASM extensions incorporating EPS concepts have been presented by Fenu *et al.*<sup>106</sup> and Xavier *et al.*<sup>107</sup> Nevertheless, it remains a challenge to accurately predict the actual EPS production. To take this into account in the ASM models, one would only have to include the fraction of EPS in the total sludge, however, a standard method for extraction and measuring EPS should first be established.<sup>98,108,109</sup> Moreover, the regulation and kinetics of EPS formation by activated and granular sludge microorganisms are also still unknown.

## 2.6 Summary

Listed in Table 1 is the summary of fundamental modelling concepts for each resource discussed in this paper and recommendations on how to address the associated needs. These are not solely recommendations directly related to modelling but also includes recommendations on focus of future research on resource recovery, which will impact and/or require modelling efforts.

**Table 1.** Key concepts for resource recovery modelling and recommendations on associated future research and modelling efforts.

Recoverable resource	Key concepts to be modelled	Recommendations – priority research topics
Energy		
Biogas	Energy content of wastewater (organics) measured as COD, more specifically biodegradable particulate COD and active biomass fractions, which are converted to methane during anaerobic digestion	Dedicated influent characterization
	The capture of COD in the produced sludge and effluent of the A-stage	Colloidal fraction consideration Flocculation and flocs settling, affected by e.g. inlet mixing phenomena for A-stage clarifiers Parameter estimation and validation for A-stage models (bioreactor+ settler)
Heat	Heat balances for temperature prediction Economic viability of heat recovery	Cost analysis

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Balancing between heat recovery and on-site or off-site heat demand

Nutrients		
Phosphate	Phosphorus-related microbial ecology and chemistry	Include appropriate level of microbial diversity in models
	Interaction of phosphorus with sulfur and iron	Coupling P-models with aqueous phase chemistry and precipitation models including S and Fe (model validation) Consider oxidation and reduction of metals involved in P recovery Better assessment of organic P mineralization in digesters Include product quality in existing phosphorus recovery models Life cycle analysis and cost analysis
Nitrogen	Amount of recoverable nitrogen in the sludge	ASMs Factors affecting organic N mineralization during anaerobic (co-)digestion
	Unit processes for nitrogen recovery (e.g. ammonia stripping, struvite precipitation, ion exchange, nanofiltration)	Develop dedicated models for N recovery
Sulfate/ Sulfur	Nitrogen recovery as microbial protein	Factors influencing N removal efficiencies of microalgal-based wastewater treatment Life cycle analysis and cost analysis of N recovery in different product forms
	Sulfur biological and/or chemical transformations (oxidation and reduction) during wastewater treatment	Coupling S-models with aqueous phase chemistry and precipitation models including P and Fe (model validation)
	When applicable, consider interactions with phosphorus and iron	
	Unit processes for sulfur recovery	Develop dedicated models for S recovery, considering which form of sulfur to be recovered



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## 4 CONCLUSIONS

- Despite being a simplification of reality, the ASMs remain state-of-the-art for modelling conventional WWTP processes and can even be used to describe significant part of the resource (energy, nutrients, and other products) recovery options.
- Extensions to the ASMs (e.g. to describe cellulose and sulfur recovery) or entirely dedicated new types of models (e.g. to describe heat and struvite recovery) may be needed for dedicated processes. There is certainly a need to better understand how and what we recover at the treatment plant of a local city or a local region, and for that, different types of models could be needed for the unit processes.
- Steady state models or even just stoichiometric models can be adequate to describe most recovery processes and cost analysis. Dynamic models are useful for optimizing individual processes and gaining more insight in process behaviours.
- A good resource recovery model should be able to predict product specifications, similar as how the effluent quality is assessed for wastewater treatment models.
- As we progress towards operating resource recovery facilities, integrated models are essential to make overall balanced evaluations. These integrated models should not only describe the treatment and recovery processes, but also assess life cycle, product quality and techno-economical aspects as additional important criteria associated with product formation.

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## 6 REFERENCES

- 1 K. Ashley, D. Cordell and D. Mavinic, A brief history of phosphorus: from the philosopher's stone to nutrient recovery and reuse, *Chemosphere*, 2011, **84**(6), 737-746.
- 2 F. de Bas, De uitkomsten van het Liernur-stelsel te Amsterdam, *De Economist*, 1882, **31**(1), 409-425.
- 3 M. Henze, W. Gujer, T. Mino, and M. C. M. van Loosdrecht, *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*. London, UK. IWA Publishing, 2000.

## Environmental Science: Water Research &amp; Technology

- 4 K. V. Gernaey, M. C. M. van Loosdrecht, M. Henze, M. Lind and S. B. Jorgensen, Activated sludge wastewater treatment plant modelling and simulation: state of the art, *Environ Model Softw*, 2004, **19**(9), 763-783.
- 5 E. I. P. Volcke, M. C. M. van Loosdrecht and P. A. Vanrolleghem, Continuity-based model interfacing for plant-wide simulation: A general approach, *Water Res.*, 2006, **40**(15), 2817-2828.
- 6 J. P. van der Hoek, H. de Fooij and A. Strucker, Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater, *Resour. Conserv. Recycl.*, 2016, **113**, 53-64.
- 7 D. Butler and M. Schütze, Integrating simulation models with a view to optimal control of urban wastewater systems, *Environ Model Softw*, 2005, **20**(4), 415-426.
- 8 A. B. de Faria, M. Spérandio, A. Ahmadi and L. Tiruta-Barna, Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA), *Water Res.*, 2015, **84**, 99-111.
- 9 J. Wan, J. Gu, Q. Zhao and Y. Liu, COD capture: a feasible option towards energy self-sufficient domestic wastewater treatment, *Sci Rep*, 2016, **6**, 25054.
- 10 G. A. Ekama, S. W. Sötemann and M. C. Wentzel, Biodegradability of activated sludge organics under anaerobic conditions, *Water Res.*, 2007, **41**(1), 244-252.
- 11 D. Ikumi, T. Harding and G. A. Ekama, Biodegradability of wastewater and activated sludge organics in anaerobic digestion, *Water Res.*, 2014, **56**, 267-279.
- 12 U. Zaher, R. Li, U. Jeppsson, J. -P. Steyer and S. Chen, GISCOD: general integrated solid waste co-digestion model, *Water Res.*, 2009, **43**(10), 2717-2727.
- 13 J. Jimenez, M. Miller, C. Bott, S. Murthy, H. De Clippeleir and B. Wett, High-rate activated sludge system for carbon management - Evaluation of crucial process mechanisms and design parameters, *Water Res.*, 2015, **87**, 476-482.
- 14 J. Smitshuijzen, J. Pérez, O. Duin and M. C. M. van Loosdrecht, A simple model to describe the performance of highly-loaded aerobic COD removal reactors, *Biochem. Eng. J.*, 2016, **112**, 94-102.
- 15 T. Nogaj, A. Randall, J. Jimenez, I. Takacs, C. Bott, M. Miller, S. Murthy and B. Wett, Modeling of organic substrate transformation in the high-rate activated sludge process, *Water Sci. Technol.*, 2015, **71**(7), 971-979.
- 16 M. de Graaff and K. Roest, *Inventarisatie van AB-systemen - Optimale Procescondities in de A-trap*. Amersfoort. The Netherlands. STOWA, 2012.
- 17 E. Torfs, Different settling regimes in secondary settling tanks: experimental process analysis, model development and calibration, *PhD thesis*, Ghent University, Ghent, Belgium, 2015.
- 18 S. S. Cipolla and M. Maglionico, Heat recovery from urban wastewater: Analysis of the variability of flow rate and temperature, *Energy Build*, 2014, **69**, 122-130.
- 19 G. Neugebauer, F. Kretschmer, R. Kollmann, M. Narodoslowsky, T. Ertl and G. Stoegelehner, Mapping thermal

- energy resource potentials from wastewater treatment plants, *Sustainability*, 2015, **7**(10), 12988-13010.
- 20 X. Zhao, L. Fu, S. Zhang, Y. Jiang and Z. Lai, Study of the performance of an urban original source heat pump system, *Energy Convers Manag*, 2010, **51**(4), 765-770.
- 21 N. Funamizu, M. Iida, Y. Sakakura and T. Takakuwa, Reuse of heat energy in wastewater: implementation examples in Japan, *Water Sci. Technol.*, 2001, **43**(10), 277-285.
- 22 A. -M. Tillman, M. Svingby and H. Lundström, Life cycle assessment of municipal waste water systems, *Int J Life Cycle Assess*, 1998, **3**(3), 145-157.
- 23 S. Gillot and P. A. Vanrolleghem, Equilibrium temperature in aerated basins—comparison of two prediction models, *Water Res.*, 2003, **37**(15), 3742-3748.
- 24 P. E. Sedory and M. K. Stenstrom, Dynamic prediction of wastewater aeration basin temperature, *J Environ Eng*, 1995, **121**(9), 609-618.
- 25 L. Corbala-Robles, E. I. P. Volcke, A. Samijn, F. Ronsse and J. G. Pieters, Effect of foam on temperature prediction and heat recovery potential from biological wastewater treatment, *Water Res.*, 2016, **95**, 340-347.
- 26 T. Fernández-Arévalo, I. Lizarralde, P. Grau and E. Ayesa, New systematic methodology for incorporating dynamic heat transfer modelling in multi-phase biochemical reactors, *Water Res.*, 2014, **60**, 141-155.
- 27 L. Corbala-Robles, F. Ronsse, J. G. Pieters and E. I. P. Volcke, Heat recovery during treatment of highly concentrated wastewater: economic evaluation and influencing factors, *Water Sci. Technol.*, 2019, **78**(11), 2270-2278.
- 28 J. M. Bloemendal, The hidden side of cities: Methods for governance, planning and design for optimal use of subsurface space with ATES, *PhD thesis*, Delft Technical University, Delft, the Netherlands, 2018.
- 29 Parsons, S., & Doyle, J. (2004). Struvite scale formation and control. *Water Sci. Technol.*, **49**(2), 177-182.
- 30 Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.*, **571**, 522-542.
- 31 H. Hauduc, I. Takács, S. Smith, A. Szabo, S. Murthy, G. Daigger and M. Spérandio, A dynamic physicochemical model for chemical phosphorus removal, *Water Res.*, 2015, **73**, 157-170.
- 32 J. Santos, L. Rieger, A. B. Lanham and A. Oehmen, *The META-ASM model: A novel approach for modelling EBPR systems*. Paper presented at the 6<sup>th</sup> IWA/WEF Water Resource Recovery Modelling Seminar (WRRmod2018), Québec, Canada, 2018 Mar 10-14.
- 33 T. Zhang, Q. Li, L. Ding, H. Ren, K. Xu, Y. Wu and D. Sheng, Modeling assessment for ammonium nitrogen recovery from wastewater by chemical precipitation, *J Environ Sci*, 2011, **23**(6), 881-890.
- 34 D. L. Parkhurst and C. A. J. Appelo, Description of Input and Examples for PHREEQC Version 3 - A Computer Program for Speciation, Batch-reaction, One-dimensional Transport, and Inverse Geochemical Calculations. U.S. Geological Survey Techniques and Methods, available only at <https://pubs.usgs.gov/tm/06/a43/>, 2013.
- 35 C. Vaneckhaute, F. H. A. Claeys, F. M. G. Tack, E. Meers, E. Belia and P. A. Vanrolleghem, Development, implementation, and validation of a generic nutrient recovery model (NRM) library, *Environ Model Softw*, 2018, **99**, 170-209.
- 36 X. Flores-Alsina, C. Kazadi Mbamba, K. Solon, D. Vrecko, S. Tait, D. J. Batstone, U. Jeppsson and K. V. Gernaey, A plant-wide aqueous phase chemistry module describing pH variations and ion speciation/pairing in wastewater treatment process models, *Water Res.*, 2015, **85**, 255-265.
- 37 C. Kazadi Mbamba, X. Flores-Alsina, D. J. Batstone, S. Tait, Validation of a plant-wide phosphorus modelling approach with minerals precipitation in a full-scale WWTP, *Water Res.*, 2016, **100**, 169-183.
- 38 L. Lizarralde, T. Fernández-Arévalo, C. Brouckaert, P.A. Vanrolleghem, D. Ikumi, G. A. Ekama, E. Ayesa and P. Grau, A new general methodology for incorporating physico-chemical transformations into multi-phase wastewater treatment process models, *Water Res.*, 2015, **74**, 239-256.
- 39 D. J. Batstone, Y. Amerlinck, G. A. Ekama, R. Goel, P. Grau, B. Johnson, I. Kaya, J. -P. Steyer, S. Tait, I. Takacs, P. A. Vanrolleghem, C. J. Brouckaert and E. I. P. Volcke, Towards a generalized physicochemical framework, *Water Sci. Technol.*, 2012, **66**(6), 1147-1161.
- 40 X. Flores-Alsina, K. Solon, C. Kazadi Mbamba, S. Tait, K. V. Gernaey, U. Jeppsson and D. J. Batstone, Modelling phosphorus (P), sulfur (S) and iron (Fe) interactions for dynamic simulations of anaerobic digestion processes, *Water Res.*, 2016, **95**, 370-382.
- 41 K. Solon, X. Flores-Alsina, C. Mbamba, D. Ikumi, E. I. P. Volcke, C. Vaneckhaute, G. A. Ekama, P. A. Vanrolleghem, D. J. Batstone, K. V. Gernaey and U. Jeppsson, Plant-wide modelling of phosphorus transformations in wastewater treatment systems: Impacts of control and operational strategies, *Water Res.*, 2017, **113**, 97-110.
- 42 P. K. Wilfert, A. Mandalidis, A. I. Dugulan, K. Goubitz, L. Korving, H. Temmink, G. J. Witkamp and M. C. M. van Loosdrecht, Vivianite as an important iron phosphate precipitate in sewage treatment plants, *Water Res.*, 2016, **104**, 449-460.
- 43 P. K. Wilfert, Phosphate Recovery From Sewage Sludge Containing Iron Phosphate, *PhD thesis*, Delft Technical University, Delft, the Netherlands, 2018.
- 44 K. S. Le Corre, E. Valsami-Jones, P. Hobbs and S. A. Parsons, Phosphorus recovery from wastewater by struvite crystallization: A review, *Crit. Rev. Environ. Sci. Technol.*, 2009, **39**(6), 433-477.
- 45 M. Franz, Phosphate fertilizer from sewage sludge ash (SSA), *Waste Management*, 2008, **28**(10), 1809-1818.
- 46 F. Rubio-Rincón, L. Welles, C. M. Lopez-Vazquez, M. Nierychlo, B. Abbas, M. Geleijnse, P. H. Nielsen, M. C. M. van Loosdrecht and D. Brdjanovic, Long-term effects of sulphide on the



## PERSPECTIVES

- enhanced biological removal of phosphorus: the symbiotic role of *Thiothrix caldifontis*, *Water Res.*, 2017, **116**, 53-64.
- 47 W. -y. Huang, *Impact of Rising Natural Gas Prices on U.S. Ammonia Supply*. USA. US Department of Agriculture, 2007.
- 48 IEA (International Energy Agency), *Tracking Industrial Energy Efficiency and CO<sub>2</sub> Emissions*. Paris, France. Organisation for Economic Co-operation and Development (OECD) / International Energy Agency (IEA), 2007.
- 49 J. W. Erisman, M. A. Sutton, J. Galloway, Z. Klimont and W. Winiwarter, How a century of ammonia synthesis changed the world, *Nature Geoscience*, 2008, **1**(10), 636.
- 50 EIA (US Energy Information Administration), *Oil and Natural Gas Resources and Technology: Issue in Focus from the Annual Energy Outlook 2018*. Washington DC, USA. US Department of Energy, 2018.
- 51 M. Maurer, J. Muncke and T. A. Larsen, Technologies for nitrogen recovery and reuse. In: P. Lens, L.H. Pol, P.A. Wilderer, & T. Asano (Eds.), *Water Recycling and Resource Recovery in Industry*. London, UK. IWA Publishing, 2002.
- 52 G. Langergraber and E. Muellegger, Ecological Sanitation - a way to solve global sanitation problems? *Environment International*, 2005, **31**(3), 433-444.
- 53 J. Lienert and T. A. Larsen, High acceptance of urine source separation in seven European countries: a review, *Environmental Science & Technology*, 2009, **44**(2), 556-566.
- 54 M. Maurer, W. Pronk and T. A. Larsen, Treatment processes for source-separated urine, *Water Res.*, 2006, **40**(17), 3151-3166.
- 55 W. Pronk, H. Palmquist, M. Biebow and M. Boller, Nanofiltration for the separation of pharmaceuticals from nutrients in source-separated urine, *Water Res.*, 2006, **40**(7), 1405-1412.
- 56 J. A. Wilsenach, C. Schuurbijs and M. C. M. van Loosdrecht, Phosphate and potassium recovery from source separated urine through struvite precipitation, *Water Res.*, 2007, **41**(2), 458-466.
- 57 M. Maurer, P. Schwegler and T. A. Larsen, Nutrients in urine: energetic aspects of removal and recovery, *Water Sci. Technol.*, 2003, **48**(1), 37-46.
- 58 M.-K. Winkler, M. Bennenbroek, F. Horstink, M. C. M. van Loosdrecht and G. -J. Van de Pol, The biodrying concept: An innovative technology creating energy from sewage sludge, *Bioresour. Technol.*, 2013, **147**, 124-129.
- 59 E. Rada, A. Franzinelli, M. Taiss, M. Ragazzi, V. Panaitescu and T. Apostol, Lower heating value dynamics during municipal solid waste bio-drying, *Environ Technol*, 2007, **28**(4), 463-469.
- 60 R. W. Melse and N. Ogink, Air scrubbing techniques for ammonia and odor reduction at livestock operations: Review of on-farm research in the Netherlands, *Trans ASAE*, 2005, **48**(6), 2303-2313.
- 61 E. Becker, Micro-algae as a source of protein, *Biotechnology Advances*, 2007, **25**(2), 207-210.
- 62 T. Hülsen, K. Hsieh, Y. Lu, S. Tait and D. J. Batstone, Simultaneous treatment and single cell protein production from agri-industrial wastewaters using purple phototrophic bacteria or microalgae - A comparison, *Bioresour. Technol.*, 2018, **254**, 214-223. DOI: 10.1039/C8EW00765A
- 63 S. Matassa, D. J. Batstone, T. Hülsen, J. Schnoor and W. Verstraete, Can direct conversion of used nitrogen to new feed and protein help feed the world? *Environ. Sci. Technol.*, 2015, **49**(9), 5247-5254.
- 64 I. Pikaar, S. Matassa, B. L. Bodirsky, I. Weindl, F. Humpeöder, K. Rabaey, N. Boon, M. Cruschi, Z. Yuan, H. van Zanten, M. Herrero, W. Verstrate and A. Popp, Decoupling livestock from land use through industrial feed production pathways, *Environ. Sci. Technol.*, 2018, **52**(13), 7351-7359.
- 65 T. Cai, S. Y. Park and Y. Li, Nutrient recovery from wastewater streams by microalgae: status and prospects, *Renew Sustain Energy Rev*, 2013, **19**, 360-369.
- 66 Z. Rasouli, B. Valverde-Pérez, M. D'Este, D. De Francisci and I. Angelidaki, Nutrient recovery from industrial wastewater as single cell protein by a co-culture of green microalgae and methanotrophs, *Biochem. Eng. J.*, 2018, **134**, 129-135.
- 67 B. Decostere, N. Janssens, A. Alvarado, T. Maere, P. Goethals, S. W. Van Hulle and I. Nopens, A combined respirometer-titrimeter for the determination of microalgae kinetics: Experimental data collection and modelling, *Chem Eng J*, 2013, **222**, 85-93.
- 68 A. Solimeno and J. García, Microalgae-bacteria models evolution: From microalgae steady-state to integrated microalgae-bacteria wastewater treatment models - A comparative review, *Sci. Total Environ.*, 2017, **607**, 1136-1150.
- 69 A. Solimeno, R. Samsó, E. Uggetti, B. Sialve, J. -P. Steyer, A. Gabarró and J. García, New mechanistic model to simulate microalgae growth, *Algal Res*, 2015, **12**, 350-358.
- 70 D. S. Wágner, B. Valverde-Pérez, M. Sæbø, M. B. de la Sotilla, J. Van Wagenen, B. F. Smets and B. G. Plósz, Towards a consensus-based biokinetic model for green microalgae-The ASM-A, *Water Res.*, 2016, **103**, 485-499.
- 71 J. Zambrano, I. Krustok, E. Nehrenheim and B. Carlsson, A simple model for algae-bacteria interaction in photo-bioreactors, *Algal Res*, 2016, **19**, 155-161.
- 72 H. Lu, J. Wang, S. Li, G. -H. Chen, M. C. M. van Loosdrecht and G. A. Ekama, Steady-state model-based evaluation of sulfate reduction, autotrophic denitrification and nitrification integrated (SANI) process, *Water Res*, 2009, **43**(14), 3613-3621.
- 73 D. Puyol, D. J. Batstone, T. Hülsen, S. Astals, M. Peces and J. O. Krömer, Resource recovery from wastewater by biological technologies: opportunities, challenges, and prospects, *Front Microbiol*, 2017, **7**, 2106.
- 74 O. Gutierrez, D. Park, K. R. Sharma and Z. Yuan, Iron salts dosage for sulfide control in sewers induces chemical phosphorus removal during wastewater treatment, *Water Res.*, 2010, **44**(11), 3467-3475.
- 75 H. Hauduc, T. Wadhawan, B. Johnson, C. Bott, M. Ward and I. Takács, Incorporating sulfur reactions and interactions with iron and phosphorus into a general plant-wide model, *Water Sci. Technol.*, 2018 (in press) <https://doi.org/10.2166/wst.2018.482>.



- 76 C. Ruiken, G. Breuer, E. Klaversma, T. Santiago and M. C. M. van Loosdrecht, Sieving wastewater - Cellulose recovery, economic and energy evaluation, *Water Res.*, 2013, **47**(1), 43-48.
- 77 J. P. van der Hoek, H. de Fooij and A. Struker, Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater, *Resour Conserv Recycl*, 2016, **113**, 53-64.
- 78 O. Nowak, K. Svardal, A. Franz and V. Kuhn, Degradation of particulate organic matter—a comparison of different model concepts, *Water Sci. Technol.*, 1999, **39**(1), 119-127.
- 79 C. Reijnen, S. Giorgi, C. Hurkmans, J. Pérez and M. C. M. van Loosdrecht, Incorporating the influent cellulose fraction in activated sludge modelling, *Water Res.*, 2018, **144**, 104-111.
- 80 M. Benneouala, Y. Bareha, E. Mengelle, M. Bounouba, M. Sperandio, Y. Bessiere and E. Paul, Hydrolysis of particulate settleable solids (PSS) in activated sludge is determined by the bacteria initially adsorbed in the sewage, *Water Res.*, 2017, **125**, 400-409.
- 81 N. Lebaz, J. Morchain, A. Cockx and M. Sperandio, Population balance approach for the modeling of enzymatic hydrolysis of cellulose, *Canadian J Chem Eng*, 2015, **93**(2), 276-284.
- 82 M. C. M. van Loosdrecht, G. A. Ekama, M. C. Wentzel, C. M. Hooijmans, C. M. Lopez-Vazquez, S. C. F. Meijer and D. Brdjanovic, Introduction to modelling of activated sludge processes. In: D. Brdjanovic, S. C. F. Meijer, C. M. Lopez-Vazquez, C. M. Hooijmans and M. C. M. van Loosdrecht (Eds.), *Applications of Activated Sludge Models*. London, UK. IWA Publishing, 2015.
- 83 J. Możejko-Ciesielska and R. Kiewisz, Bacterial polyhydroxyalkanoates: Still fabulous? *Microbiol. Res.*, 2016, **192**, 271-282.
- 84 K. D. Snell and O. P. Peoples, PHA bioplastic: A value-added coproduct for biomass biorefineries, *Biofuel Bioprod Biorefin*, 2009, **3**(4), 456-467.
- 85 G.-Q. Chen, A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry, *Chem Soc Rev*, 2009, **38**(8), 2434-2446.
- 86 R. Kleerebezem and M. C. M. van Loosdrecht, Mixed culture biotechnology for bioenergy production, *Curr. Opin. Biotechnol.*, 2007, **18**(3), 207-212.
- 87 H. Salehizadeh and M. C. M. van Loosdrecht, Production of polyhydroxyalkanoates by mixed culture: recent trends and biotechnological importance, *Biotechnol. Adv.*, 2004, **22**(3), 261-279.
- 88 S. Bengtsson, A. Werker, M. Christensson and T. Welander, Production of polyhydroxyalkanoates by activated sludge treating a paper mill wastewater, *Bioresour. Technol.*, 2008, **99**(3), 509-516.
- 89 S. Bengtsson, A. Werker, C. Visser and L. Korving, *PHARIO: Stepping Stone to a Sustainable Value Chain for PHA Bioplastic using Municipal Activated Sludge*. Amersfoort, the Netherlands. STOWA, 2017.
- 90 S. Hanada, H. Satoh and T. Mino, Measurement of microorganisms with PHA production capability in activated sludge and its implication in activated sludge model no. 3, *Water Sci. Technol.*, 2002, **45**(6), 107-113. [10.1039/C8EW00765A](https://doi.org/10.1039/C8EW00765A)
- 91 A. Guisasola, G. Sin, J. Baeza, J. Carrera and P. A. Vanrolleghem, Limitations of ASM1 and ASM3: a comparison based on batch oxygen uptake rate profiles from different full-scale wastewater treatment plants, *Water Sci. Technol.*, 2005, **52**(10-11), 69-77.
- 92 C. Fernández-Dacosta, J. A. Posada, R. Kleerebezem, M. C. Cuellar and A. Ramirez, Microbial community-based polyhydroxyalkanoates (PHAs) production from wastewater: techno-economic analysis and ex-ante environmental assessment, *Bioresour. Technol.*, 2015, **185**, 368-377.
- 93 R. M. Donlan, Biofilms: microbial life on surfaces. *Emerging Infect. Dis.*, 2002, **8**(9), 881.
- 94 P. H. Nielsen, A. Jahn and R. Palmgren, Conceptual model for production and composition of exopolymers in biofilms, *Water Sci. Technol.*, 1997, **36**(1), 11-19.
- 95 H.-C. Flemming and J. Wingender, The biofilm matrix. *Nat. Rev. Microbiol.*, 2010, **8**(9), 623.
- 96 C. S. Lapidou and B. E. Rittmann, unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass, *Water Res.*, 2002, **36**(11), 2711-2720.
- 97 Y. Jiao, G. D. Cody, A. K. Harding, P. Wilmes, M. Schrenk, K. E. Wheeler, J. F. Banfield and M. P. Thelen, Characterization of extracellular polymeric substances from acidophilic microbial biofilms, *Appl. Environ. Microbiol.*, 2010, **76**(9), 2916-2922.
- 98 T. Seviour, N. Derlon, M. S. Dueholm, H.-C. Flemming, E. Girbal-Neuhausser, H. Horn, S. Kjelleberg, M. C. M. van Loosdrecht, T. Lotti, M. F. Malpei, R. Nerenberg, T. R. Neu, E. Paul, H. Yu and Y. Lin, Extracellular polymeric substances of biofilms: Suffering from an identity crisis, *Water Res.*, 2019, **151**, 1-7.
- 99 J. Wingender, T. R. Neu and H.-C. Flemming, What are bacterial extracellular polymeric substances? In: J. Wingender, T.R. Neu and H.-C. Flemming, *Microbial Extracellular Polymeric Substances*. Heidelberg, Germany. Springer, 1999.
- 100 C. Jia, P. Li, X. Li, P. Tai, W. Liu and Z. Gong, Degradation of pyrene in soils by extracellular polymeric substances (EPS) extracted from liquid cultures, *Process Biochem*, 2011, **46**(8), 1627-1631.
- 101 Y. Tuo, G. Liu, B. Dong, J. Zhou, A. Wang, J. Wang, R. Jin, H. Lv, Z. Dou and W. Huang, Microbial synthesis of Pd/Fe<sub>3</sub>O<sub>4</sub>, Au/Fe<sub>3</sub>O<sub>4</sub> and PdAu/Fe<sub>3</sub>O<sub>4</sub> nanocomposites for catalytic reduction of nitroaromatic compounds, *Sci Rep*, 2015, **5**, 13515.
- 102 R. Mikutta, A. Baumgärtner, A. Schippers, L. Haumaier and G. Guggenberger, Extracellular polymeric substances from *Bacillus subtilis* associated with minerals modify the extent and rate of heavy metal sorption, *Environ. Sci. Technol.*, 2012, **46**(7), 3866-3873.
- 103 T. More, J. Yadav, S. Yan, R. Tyagi and R. Surampalli, Extracellular polymeric substances of bacteria and their potential environmental applications, *J. Environ. Manage.*, 2014, **144**, 1-25.

## PERSPECTIVES

- 104 Y. Lin, M. de Kreuk, M. C. M. van Loosdrecht and A. Adin, Characterization of alginate-like exopolysaccharides isolated from aerobic granular sludge in pilot-plant, *Water Res.*, 2010, **44**(11), 3355-3364.
- 105 "Kaamera", Retrieved from <https://kaamera.com>, 2018.
- 106 A. Fenu, G. Guglielmi, J. Jimenez, M. Spèrandio, D. Saroj, B. Lesjean, C. Brepols, C. Thoeve and I. Nopens, Activated sludge model (ASM) based modelling of membrane bioreactor (MBR) processes: a critical review with special regard to MBR specificities, *Water Res.*, 2010, **44**(15), 4272-4294.
- 107 J. B. Xavier, C. Picioreanu and M. C. M. van Loosdrecht, A framework for multidimensional modelling of activity and structure of multispecies biofilms, *Environ. Microbiol.*, 2005, **7**(8), 1085-1103.
- 108 M. K. De Kreuk, N. Kishida and M. C. M. van Loosdrecht, Aerobic granular sludge - state of the art, *Water Sci. Technol.*, 2007, **55**(8-9), 75-81.
- 109 S. Felz, S. Al-Zuhair, O. A. Aarstad, M. C. M. van Loosdrecht and Y. M. Lin, Extraction of structural extracellular polymeric substances from aerobic granular sludge, *J Vis Exp*, 2016, **115**: 54534.
- 110 J. Foley, D. de Haas, K. Hartley and P. Lant, Comprehensive life cycle inventories of alternative wastewater treatment systems, *Water Res.*, 2010, **44**, 1654-1666.
- 111 A. B. Bisinella de Faria, M. Spèrandio, A. Ahmadi and L. Tiruta-Barna, Evaluation of new alternatives in wastewater treatment plants based on Dynamic Modelling and Life Cycle Assessment (DM-LCA), *Water Res.*, 2015, **84**, 99-111.
- 112 M. Arnell, M. Rahmberg, F. Oliveira and U. Jeppsson, Multi-objective performance assessment of wastewater treatment plants combining plant-wide process models and life cycle assessment, *J Water Clim Change*, 2017, **8**(1), 715-729.
- 113 M. Arnell, S. Astals, L. Åmand, D. J. Batstone, P. D. Jensen and U. Jeppsson, Modelling anaerobic co-digestion in Benchmark Simulation Model No. 2: parameter estimation, substrate characterisation and plant-wide integration, *Water Res.*, 2016, **98**, 138-146.
- 114 R. Khiewwijit, H. Temmink, H. Rijnaarts and K. J. Keesman, Energy and nutrient recovery for municipal wastewater treatment: how to design a feasible plant layout? *Environ Model Softw*, 2015, **68**, 156-165.
- 115 G. Langergraber, L. Rieger, S. Winkler, J. Alex, J. Wiese, C. Owerdieck, M. Ahnert, J. Simon and M. Maurer, A guideline for simulation studies of wastewater treatment plants, *Water Sci. Technol.*, 2004, **50**(7), 131-138.
- 116 X. Flores-Alsina, M. Arnell, Y. Amerlinck, L. Corominas, K. V. Gernaey, L. Guo, E. Lindblom, I. Nopens, J. Porro, A. Shaw, L. Snip, P. A. Vanrolleghem and U. Jeppsson, Balancing effluent quality, economic cost and greenhouse gas emissions during the evaluation of (plant-wide) control/operational strategies in WWTPs, *Sci. Total Environ.*, 2014, **466-467**, 616-624.
- 117 T. Fernández-Arévalo, I. Lizarralde, F. Fdz-Polanco, S. I. Pérez-Elvira, J. M. Garrido, S. Puig, M. Poch and E. Ayesa, Quantitative assessment of energy and resource recovery in wastewater treatment plants based on plant-wide simulations, *Water Res.*, 2017, **118**, 272-288. DOI: 10.1039/C8EW00765A
- 118 J. A. Wilsenach and M. C. M. van Loosdrecht, Integration of processes to treat wastewater and source-separated urine, *J Environ Eng*, 2006, **132**(3), 331-341.
- 119 S. K. L. Ishii and T. H. Boyer, Life cycle comparison of centralized wastewater treatment and urine source separation with struvite precipitation: Focus on urine nutrient management, *Water Res.*, 2015, **79**, 88-103.
- 120 E. Igos, M. Besson, T. Navarrete Gutiérrez, A. B. Bisinella de Faria, E. Benetto, L. Barna, A. Ahmadi and M. Spèrandio, Assessment of environmental impacts and operational costs of the implementation of an innovative source-separated urine treatment, *Water Res.*, 2017, **126**, 50-59.
- 121 N. Guriëff and P. Lant, Comparative life cycle assessment and financial analysis of mixed culture polyhydroxyalkanoate production, *Bioresour. Technol.*, 2007, **98**, 3393-3403.
- 122 A. B. Bisinella de Faria, A. Ahmadi, L. Tiruta-Barna and M. Spèrandio, Feasibility of rigorous multi-objective optimization of wastewater management and treatment plants, *Chem Eng Res Des*, 2016, **115**, 394-406.