Resource recovery from waste streams: from LIFE LIVEWASTE to H2020 SMART-Plant

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The LIFE LIVEWASTE project (www.livewaste.org) has demonstrated how livestock effluents (e.g. manure and slurry) are key streams where the circular economy strategies must be applied to recover fertilizer precursors, soil improvers, biofuels, water. On the other hand, municipal wastewater is not secondary when circular economy in the water sector is considered.

Wastewater treatment is a growing segment of the water industry, which has been subjected to decades of continuous tightening of water quality regulations. At present, **about 22000 municipal wastewater treatment plants (WWTPs) with treatment capacity >2000 inhabitants are operational in the 28 EU member states**, Iceland, Norway and Switzerland. By 2017, **investments** in European WWTPs are expected to reach **37.6 billion euro**. Growth will be the most dynamic in Southern and Eastern Europe.[1] By contrast, maintenance and renewals and measures to reduce operational costs (primarily energy related) will dominate in Central and Northern Europe. The EU Urban Waste Water Treatment Directive and the EU Water Framework Directive (WFD) will remain the most important driving Legislation for new construction and upgrading measures in existing WWTPs. The former EU member states, which were supposed to comply with directive specifications by the end of 2005, have still to invest significant resources in order to upgrade and adjust their wastewater treatment infrastructures as required by the enforced regulations. For instance, the European Court of Justice sanctioned Italy in 2012 to subsequently improve the wastewater treatment in more than 80 settlement areas[2]. In such a market scenario, **the scope for innovation in municipal WWTPs is strategic incremental**, although there remains the opportunity to optimise essentially mature technologies. **Key barriers to exploitation of innovations in wastewater treatment sector** are not only the lack of incentives, but also the **risk aversion of water utilities or end-users in moving from conventional, low-efficiency treatment systems to high-rate, high-efficiency technologies with embedded additional benefits from recovery of resources**. Partnerships among technology providers, water utilities and authorities and research organizations will be key success factors for overcoming such a risk aversion by providing validation and demonstration, thus resulting in suitable **Water Public Innovation Procurement Policies** or **public-private governance alternatives**.

Besides the compliance with tight water-related European regulations, the need to be **more efficient with the use and recovery of resources, energy efficiency and release of greenhouse gases (GHG)** has become a central issue in municipal WWTPs. Extracting resources from wastewater is not new. Generating energy from digester biogas is one way to extract resources from what should be considered **"used" water rather than "waste" water**. Producing fit-for-purpose water and beneficial use of biosolids have also become accepted in the wastewater treatment industry. However, even the application of proven technologies (to reuse water, biogas, organic fertilizers, nutrients) is not widespread, although the amount of waste available to be reused is 28 Kg per inhabitant per year, for a total of about 20 million tons per year in Europe, otherwise generating costs of water treatment as high as €25-30 per inhabitant per year.

The main bottleneck for energy-efficiency and resource recovery is the **dilution** of raw municipal wastewater that involves energy-intensive **aerobic** biological treatment as a core technology to reach the environmental quality standard for the treated wastewater. Therefore, we must shift from traditional aerobic to innovative **energy-efficient anaerobic-aerobic** biotechnologies, from one side, and apply primary **upstream concentration** and post-treatment of high- and low-solid primary effluents, from the other side. Once these approaches are followed, key enabling technologies that extracts resources will be sustainable and lead to economic cumulative benefits higher than about € 17-18 per inhabitant per year for large plants, of which about 50% is derived from resource recovery. The resource recovery techniques include the **biological upgrading of the organic carbon contained in sewage to polyhydroxyalkanoates (PHA),** biopolymers that can be used for manufacturing of biodegradable thermoplastics, **phosphorus recovery as struvite or organic fertilizer (P-rich compost),** to produce slow-release fertilizer, and **cellulose fibres recovery**, mainly originating from toilet paper in wastewater.

[1] http://www.researchandmarkets.com/research/djcdzb/market_study

[2] http://ec.europa.eu/environment/legal/law/press_en.htm

A number of wastewater treatment unit processes have reached the proof of concept and, in order to succeed, will be able to cross the "valley of death"[3] only if a real value is captured and demonstrated, so as to be financed for widespread application. **In light of this, the key for innovation uptake stands in upgrading the existing WWTPs by integrating case-adequate novel operation units** without revolutionizing the existing system, thus requiring an initial investment of € 15-20 per inhabitant with one year payoff through potential cumulative savings of € 17-18 per inhabitant per year.
In particular, innovative systems should bring clear advantages towards the **energy-efficient achievement of water-quality regulatory standards, while being able to recover resources, which are lost otherwise.** Then, **a superstructure approach will support the decision** to integrate these innovative operation units in complete, best available technical solutions, which will ultimately lead to a paradigm shift from wastewater treatment **towards resource recovery facilities**.

The global objective of the Horizon2020 **SMART-plant Innovation Action ("**Scale-up of low-carbon footprint material recovery techniques in existing wastewater treatment plants" "SMART-Plant" – GA n. 690323**) is to support the water sector to improve and ensure environmental protection, become more adaptive, and respond to contemporary environmental and societal challenges** by introducing innovative technological solutions, moving towards resource recovery approaches in wastewater management. To reach this goal, **SMART-plant will scale-up and demonstrate eco-innovative solutions** to upgrade existing WWTPs. This will be accomplished by applying low-carbon footprint technologies to provide high-quality treated water and recover materials that are otherwise lost, in order to demonstrate the **viability of the full recycle chain**. The project will contribute to the change in the nowadays water utility management perspectives towards resource recovery.

The overall target of SMART-Plant is to validate and to address to the market a portfolio of SMARTechnologies that, singularly or combined, can renovate and upgrade existing wastewater treatment plants and give the added value of instigating the paradigm change towards efficient wastewater-based bio-refineries.

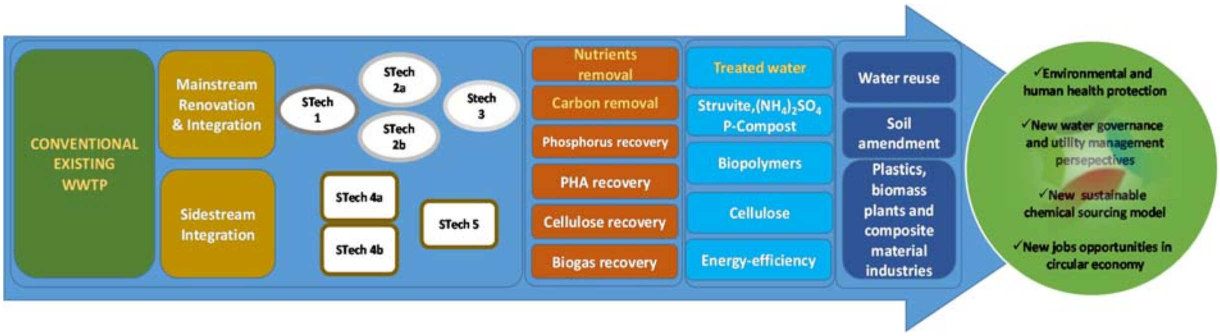

Figure 1 *SMART-plant concept and targets*

To meet the overall target, the specific project objectives (SOs) are as follows:

[3] M. Cermerón et al (2013) "Ecosistema de innovación sostenible. El conocimiento circular. La Transferencia de Tecnología Universidad - Empresa. Nuevos instrumentos y horizontes. Fundación CYD.

Table 1 *Specific Objectives of SMART-Plant*

Specific Objective (SO)
"PLUG-AND-TREAT" TECHNOLOGIES: To integrate and start-up seven scaled-up synergic innovative SMARTechnologies that can upgrade typical existing municipal WWTPs without radical changes of the existing asset of the operational management
TECHNOLOGY PERFORMANCE: To validate the long term operational viability of each single SMARTechnology by operating the units for 2 years, meeting the treatment performances, resource recovery yield and maintenance or betterment of existing quality of treated effluent
Evaluation through EU ETV pilot programme: To provide regulators, water utilities and industry with a comprehensive technical, environmental and economic monitoring data set to facilitate the uptake of technologies and recovered resources. SMART-Plant will engage with the EU Environmental Technology Verification (ETV) pilot programme to validate and verify output
ROBUST ICT: To accomplish a high level of automation, real-time monitoring and control of the processes through application of low-cost sensors. The systems will also be integrated with: (a) novel sensors for in situ VFA measurements; (b) real-time energy consumptions; (c) tool for on-line carbon footprint calculation
MONITORING AND IMPROVEMENT OF ENERGY EFFICIENCY: To demonstrate carbon footprint reduction and energy savings through the implementation of SMARTechnologies
ENVIRONMENTAL AND SOCIO-ECONOMIC BENEFITS: To validate the systems in environmental and economic terms and demonstrate its social acceptability
DEDICATED SOFTWARE PLATFORM FOR PROCESS INTEGRATION: To provide validated software platforms and technical support to facilitate the design and optimal operation of SMARTechnologies
CLOSING OF THE CIRCULAR VALUE CHAIN: To develop and validate n.2 downstream SMARTechnologies and the exploitation plan for the SMART-product portfolio for the recovered resources
IMPROVE THE WATER TREATMENT ECONOMICS: To integrate in a single platform advanced technologies that can generate biogas used as energy source for operations, and additional recovery of SMART-product portfolio of chemical feedstock
MORE SUSTAINABLE COMPLIANCE WITH EU DIRECTIVEs: upgrade existing assets, with low initial investment, thus reducing costs of compliance to 91/271/ECC for the 15% of European UWWTPs lagging behind and bringing them to a level beyond the Urban Waste Water Treatment Directive with respect to the level of pollutants, product recovery and carbon footprint
FINANCING INNOVATION: to introduce substantial innovation in the public water sector, providing a solution overcoming the cost barrier for adoption of innovation and offering additional versatility through an integrated technological platform.
INCENTIVE-BASED PUBLIC ACCEPTANCE: To lead to water price adaptation for households, as a consequence of the reduced operational costs for water treatment and additional benefits from marketing recovered resources.
EXTENDED MARKET OUTREACH: to enable recovery of chemical resources derived from materials otherwise wasted, to be used by industry, thus increasing competitiveness of European chemicals and down-stream industry sectors by availability of low price domestic feedstock sources and reducing their dependability on non-domestic feedstock sources, with possibility to increase capacity by extending the use of the SMARTechs to municipal solid waste.
PUBLIC-PRIVATE PARTNESHIP: to facilitate public-private partnership introducing a model that brings together the public water sector with private chemicals and downstream chemical processing industry.
LINK WATER AND CHEMICAL VALUE CHAIN: To strengthen European innovation as it relates to the water and the chemical value chains.
JOBs CREATION: SMART-Plant will generate new employment related to water technology in European countries.
STAKEHOLDER AND CITIZENS INVOLVEMENT: will mobilize strong partnerships between SMEs, industry, research community and public authorities, regulators, water utilities and the public, engaging with and educating the public particularly on accepting even "used" water as a highly valuable resource

SMART-plant is based on the concept that WWTPs are not only facilities for the treatment and safe disposal of wastewater and sludge, but rather factories where these *"used" streams* are converted into value-added products and renewable energy - without any extra cost, but promoting a new public-private partnership for a new water utility management perspective. This has been driven by both the stricter EU legislation aiming to protect water bodies from increasing pollution and degradation and the opportunity to provide an internal source of revenue. The project will be directed to the scale-up and application of eco-innovative, circular wastewater treatment technologies for smart use of energy, carbon and nutrients that are contained in wastewater and sludge, in order to revamp existing WWTPs in an environmentally and economically sustainable way.

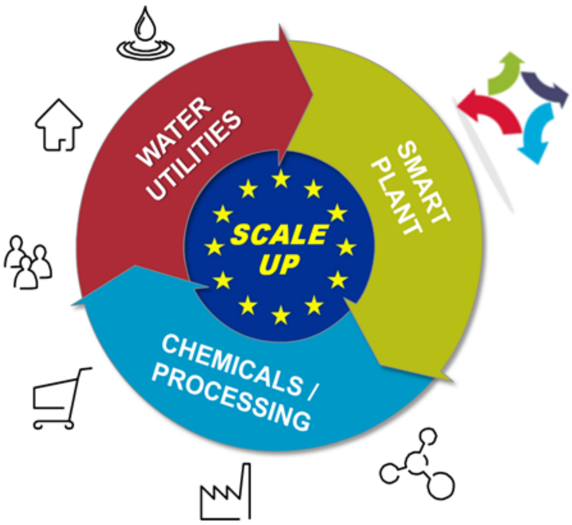

Figure 2 Schematic view of the SMART-Plant overall Concept

The SMART-Plant project does not promote a specific technology, but rather the energy efficient wastewater resource recovery concept, through the technology platform developed within existing plants to eventually prompt the development of new products and business opportunities analysed in Section 2. As the water utilities landscape is heterogeneous with respect to current level of nutrient removal and needs, SMART-Plant is proposed as a modular configuration, with the integration of several technologies in a final customizable set-up, to provide the right fit solution to different water utilities. The SMART-Plant concept is in line with EU policy on circular economy[4] and the resource efficiency agenda established under the Europe 2020 strategy for smart, sustainable and inclusive growth[5].

The project envisages the development and application of 4 innovative systems to be integrated into the wastewater treatment train (mainstream), and 3 systems to be employed for the integration of anaerobic digestion of sewage sludge (sidestream) (Figure 1.2). **All SMARTechs have two common targets: (I) to decrease energy consumption while maintaining high treated water quality** for discharge and/or reuse, and (II) to **recover valuable materials** from wastewater and sludge. These consist of: (a) P-rich compost and struvite, to be used in agriculture, (b) biologically-derived polyhydroxyalkanoates (PHA) to produce thermoplastics, (c) cellulose for construction materials and (d) fuel for biomass plants. SMART-Plant is based on **key enabling processes**, applicable singularly or combined to maximise the extraction of valuable resources from wastewater: (I) **solids up-concentration of municipal wastewater** by dynamic tunable fine-sieving; (II) **biological energy-saving anaerobic and short-cut enhanced processes (anaerobic biofilter; Short-Cut Enhanced Nutrient Abatement (S.C.E.N.A.); Short-Cut Enhanced Phosphorus and PHA Recovery (S.C.E.P.P.H.A.R.)**; (III) **innovative ion exchange** for tertiary refinement; (IV) resource recovery for agriculture or biomass plants by composting and bio-drying. Once the SMARTechs are validated, modelling of the 3 key enabling processes and the decision support systems will constitute to the SMART-Plant ICT platform that will facilitate the design and realization of single or combined SMARTechs integration in municipal WWTPs.

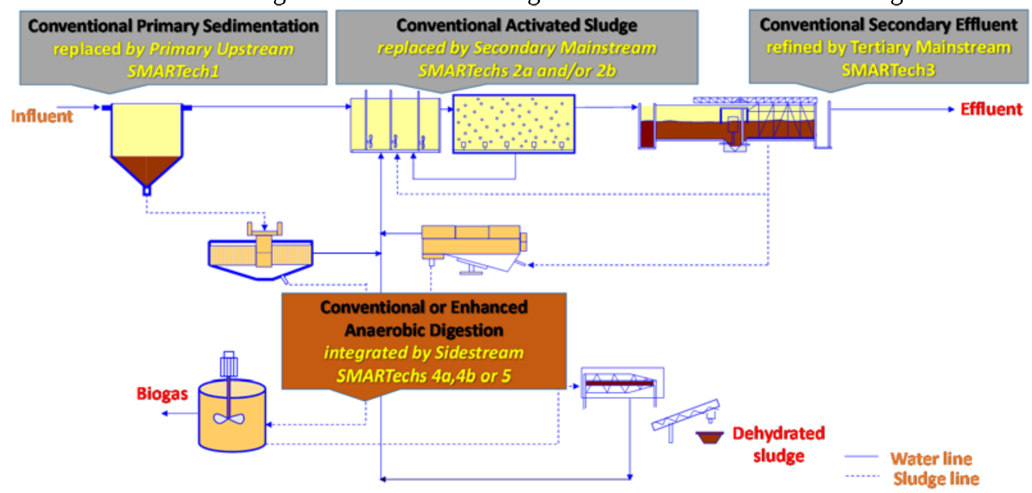

Figure 3 *SMART-Plant technology platform: approach for integration in existing conventional wastewater treatment plants*

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[4] COM. 2014. Towards a circular economy: a zero waste programme for Europe. http://eur-lex.europa.eu/resource.html?uri=cellar:aa88c66d-4553-11e4-a0cb-01aa75ed71a1.0022.03/DOC_1&format=PDF

[5] COM. 2011. A resource-efficient Europe – flagship initiative under the Europe 2020 strategy. http://ec.europa.eu/resource-efficient-europe/pdf/resource_efficient_europe_en.pdf (accessed 11th March 2014).

Table 2 *SMARTechnologies and extractable material*

SMARTech n.	**Integrated municipal WWTP**	**Key enabling process(es)**	**SMART-product(s)**
1	Uithuizermeeden (Netherlands)	Upstream dynamic fine-screen and post-processing of cellulosic sludge	Cellulosic sludge, refined clean cellulose
2a	Karmiel (Israel)	Mainstream polyurethane-based anaerobic biofilter	Biogas, Energy-efficient water reuse
2b	Manresa (Spain)	Mainstream SCEPPHAS	P-rich sludge, PHA
3	Cranfield (UK)	Mainstream tertiary hybrid ion exchange	Nutrients
4a	Carbonera (Italy)	Sidestream SCENA+conventional AD	P-rich sludge, VFA
4b	Psyttalia (Greece)	Sidestream SCENA+enhanced AD	P-rich sludge
5	Carbonera (Italy)	Sidestream SCEPPHAR	PHA, struvite, VFA
Downstream SMARTechA	London (UK)	Formulation of recovered cellulosic and PHA materials+extrusion	Biocomposite (Sludge Plastic Composite – SPC)
Downstream SMARTechB	Manresa (Spain)	Dynamic composting of P-rich sludge using minerals as bulking agents; bio-drying of cellulosic sludge	P-rich compost, enriched with minerals; fuel for biomass plants

Once the “used” water is valorised to the SMART-product portfolio (PHA, cellulose, nutrients), the properties of the recovered resources will be characterized by ISO/EN standard and novel techniques and their route-to-market will be planned with benefits for water utilities and citizens as discussed in section 2. Since the economy of scale is a potential bottleneck of inside-WWTP resource recovery technologies, centralized outside-WWTP downstream processing of cellulosic sludge, PHA, P-rich sludge and minerals will be tested to validate the technical, economic and environmental sustainability of **the full value chain.** Besides **the marketable chemicals of the SMART-product portfolio**, the final end-products will be: (I) the sludge plastic composite for the construction sector; (II) P-rich compost; (III) struvite; (IV) cellulose; (V) fuel for biomass plants.

SMARTech1 is the key to enable primary cellulose harvesting from medium-large WWTPs. It will apply the primary concentration of wastewater by Salsnes Filter dynamic fine-sieve, which can enable maximal recovery of resources. The Salsnes Filter will separate cellulosic sludge that will be followed by post-processing inside the WWTP. The latter includes a compact sequence of operation unites imported by the paper and food industry to produce clean and marketable cellulose. The cellulosic material will be also provided outside the WWTP for the downstream blending with PHA and processing for final bio-composite production (Downstream SMARTechA).

SMARTech2a is the key to enable secondary biogas recovery from small-medium municipal WWTP where irregular organic-load peaks often occur. It will apply a secondary anaerobic biofilter with an innovative polymeric-based immobilization matrix to treat anaerobically sewage and produce biogas. The system will result in high COD and TSS removal as well as biogas production, providing treated effluent adapted for reuse in agriculture or reclamation after post-treatment. The demo system will have a reaction volume of 25 m^3 and will be installed at the municipal WWTP of Karmiel (Israel) to treat 100-120 m^3/d of sewage.

SMARTech2b is the key to enable secondary mainstream energy-efficient resource recovery. It applies the SCEPPHAR system to the mainstream treatment train. It consists of two SBR; one for heterotrophic bacterial growth, and another SBR for autotrophic nitrifiers growth, 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 will be recovered from the anaerobic purge of the SBR. The pilot-scale system will have a reaction volume of 6-8 m^3 and will be installed at the Manresa municipal WWTP (Spain) to treat about 10 m^3/d of sewage.

SMARTech3 is the key to enable tertiary recovery of N and P based fertilizer based on ion-exchange processes to remove and recover nutrients from secondary effluents. Two different ion exchange media will be applied which are able to successfully capture/remove ammonia and phosphate from the secondary effluent. To overcome the limited supply chain of the ion exchanging materials, new ion exchange media, manufactured in the UK, will be applied. The aim will be to optimize the regeneration cycles for the nutrient recovery, trying to maintain a high sorption capacity after each regeneration cycle. The system will be applied at the Cranfield municipal WWTP (UK) and will treat approximately 10-60 m^3/d.

SMARTech4a is the key to enable the integration of conventional biogas recovery from sewage sludge with sidestream energy-efficient and compact nitrogen removal and phosphorus recovery. It applies the SCENA system which integrates the following processes: (o) optional upstream concentration of cellulosic sludge, (i) fermentation of sewage sludge and/or cellulosic sludge with alkalisilcates (e.g. wollastonite) to produce propionate-rich VFAs as carbon source, and (ii) via nitrite nitrogen and phosphorus removal (by P-bioaccumulation) from sludge reject water using an SBR. In this configuration, nitrogen is removed through the

bioprocesses of nitritation/denitritation, and Enhanced Biological Phosphorus removal (EBPR) is accomplished via nitrite through the alternation of anaerobic/anoxic conditions and via oxygen through the alternation of anaerobic/aerobic conditions. The first full scale demo application to treat around 100 m^3/d of sludge reject water will be developed in the WWTP of Carbonera (Italy). It will allow the recovery and reuse of 7 kgVFA and 7-8 kg P-rich sludge per capita per year and the savings of more than 50% bioreactor volume and energy consumption from sludge reject water.
SMARTech4b is the key to enable the integration of the enhanced biogas recovery (by thermal hydrolysis) of sewage sludge with sidestream energy-efficient and compact nitrogen removal and phosphorus recovery. It modify the original SCENA concept to treat the sludge reject water in the Psyttalia WWTP of Athens, which services a population equivalent of 3,500,000 inhabitants. The CAMBI thermal hydrolysis process has been very recently installed to treat 50% of the produced sludge, before this is sent for anaerobic digestion (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). Being the sludge hydrolized for biogas production, the SCENA process that will use the primary sludge reject water as partial carbon source to remove nitrogen and hyper-accumulate phosphorus.
SMARTech5 is the key to enable the integration of conventional biogas recovery from sewage sludge with the energy-efficient nitrogen removal from sludge reject water and the recovery of PHA and struvite. It applies the SCEPPHAR concept, which was conceived as a modified version of SCENA for WWTPs larger than 150 kPE, where PHA recovery is an economically sustainable option. It accounts of the following subprocesses: (i) sewage sludge fermentation under alkaline conditions (pH around 10) to enhance the production of VFAs and release nitrogen and phosphorus in soluble forms (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 favor 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. The system is based on two SBRs for the via-nitrite nitrogen removal coupled with microbial culture enrichment, and storage of PHA in sewage sludge. The pilot-scale system will be tested and validated at WWTP Carbonera (Treviso, Italy).
Downstream SMARTechA is the key to enable the volume-utilisation of the recovered materials, both PHA bioplastics and cellulosic materials. The proposed pilot will be based on UBRUN patent technology of using recovered biodegradable resources for value added construction products. The pilot-scale production plant will be set up at Brunel by enhancing the existing composite pilot plant with the input of extruder/extrusion from Ecodek. It consists of on the modified extrusion process used for processing classical WPC as the industrial partner, Ecodek, is currently manufacturing. The existing WPC production line will be adjusted to incorporate specific thermal process and blending, and for use of additives improving interfaces among all the raw material constituents
Downstream SMARTechB is a key to enable the agronomic and Energy utilization of the cellulose and P-rich sludges. It consists of dynamic composting using different blending of P-rich sludges and zeolite where the process will be optimized using respirometry activity in the mixture. The cellulosic sludge will be post-process in biodrying process which is optimal for organic wastes of high moisture content. This consists in the utilization of thermal energy, generated by aeration degradation of organic matter in waste, to evaporate water, thus achieving self-drying. Finally the dried cellulosic sludge will be characterized to be reused as fuel in biomass plants.
To achieve the targets of SMART-plant, trans-disciplinary and inter-technology know-how transfer will take place. Various disciplines will be applied, including process engineering for the optimization of the bioprocesses, software development for the control and automation, biology and chemistry for monitoring biochemical processes and the development of the PHA extraction processes, agronomy for the studies on plant nutrition, and environmental engineering for the application of the LCA and water footprint tools.

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