



## **A research challenge vision regarding management of agricultural waste in a circular bio-based economy**

Nathalie Gontard, Ulf Sonesson, Morten Birkved, Mauro Majone, David Bolzonella, Annamaria Celli, Helene Angellier-Coussy, Guang-Way Jang, Anne Verniquet, Jan Broeze, et al.

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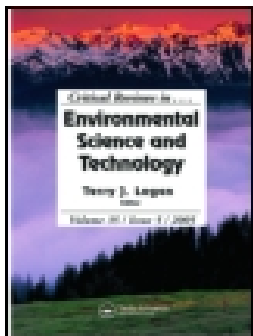
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## A research challenge vision regarding management of agricultural waste in a circular bio-based economy

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## ABSTRACT

Agricultural waste is a huge pool of untapped biomass resources that may even represent economic and environmental burdens. They can be converted into bioenergy and bio-based products by cascading conversion processes, within circular economy, and should be considered residual resources. Major challenges are discussed from a transdisciplinary perspective, focused on Europe situation. Environmental and economic consequences of agricultural residue management chains are difficult to assess due to their complexity, seasonality and regionality. Designing multi-criteria decision support tools, applicable at an early-stage of research, is discussed. Improvement of Anaerobic Digestion (AD), one of the most mature conversion technologies, is discussed from a technological point of view and waste feedstock geographical and seasonal variations. Using agricultural residual resources for producing high-value chemicals is a considerable challenge analysed here, taking into account innovative eco-efficient and cost-effective cascading conversion processes (bio-refinery concept). Moreover, the promotion of agricultural residues-based business is discussed through industrial ecology, to promote synergy, on a local basis, between different agricultural and industrial value chains. Finally, to facilitate a holistic approach and optimise materials and knowledge flows

## KEY WORDS

Agriculture; waste;  
eco-design; biogas;  
bio-based materials;  
circular economy

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management, the connection of stakeholders is discussed to promote cross-sectorial collaboration and resource exchange at appropriate geographic scales.

## Introduction

According to FAO (2011), food production and supply chains consume approximately 30% of the total global energy production, while increasing bio-energy dedicated crops are criticised for competing with food crops and hence jeopardising food security and biodiversity. Additionally, the projected 9 billion people world population by 2050 will lead to a demand for increased food production inevitably yielding a proportional increase in primary agricultural residues. In 2012, these residual resources accounted for about 50% of the fresh weight of harvested crops and represent a potential of 90 Million Tons Oil Equivalent (MTOE), far more than any other waste streams such as round wood production (57 MTOE), municipal and other waste (42 MTOE) and tertiary forest residues (32 MTOE) (Elbersen et al., 2012). Moreover, economic and environmental issues associated to agricultural primary residues are correlated with the regional specialisation (e.g. infrastructure, waste processing technologies, energy supply technologies etc.) in terms of either animal feed crop or animal production. For example, in regions devoted to animal breeding, huge amounts of manure residue are produced, resulting in intensive odours and bacteria contamination, high greenhouse gas (GHG) emissions and high organic matter and nutrients (e.g. nitrogen) loads. Meanwhile, in regions mainly devoted to vegetable crop production (e.g. for animal feed) there is a depletion of nutrients and organic matter, thus resulting in a global unbalance.

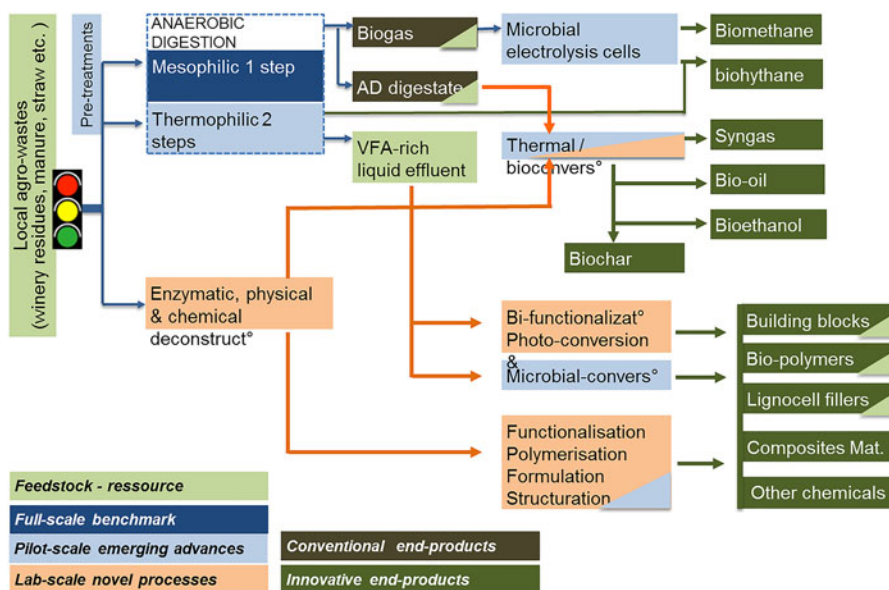
Agricultural waste, by-products and co-products are usually defined as plant or animal residues that are not (or not further processed into) food or feed, that may even be responsible for additional environmental and economic burdens in the farming and primary processing sectors. In order to further improve resource efficiency and improve agricultural waste management in primary production, it is considered of paramount importance to promote a circular economy approach. Agricultural waste is, mainly, primary residues that can be turned into resources using intensified conversion processes which may yield potentially sustainable bio-products such as fertilisers, energy, materials and molecules. The conversion of this agricultural residue is crucial for supporting the decoupling of economic growth and human well-being from (primary) resources use, preventing putting pressure on land, causing adverse effects on biodiversity and jeopardising global food security (UNEP, 2011).

Our publication aims at providing a vision covering key challenges to ensure sustainable agricultural residue utilisations, through a trans-disciplinary approach, aiming at contributing to the development of innovative holistic approaches in supporting eco-efficient conversion routes and smart agricultural residue management strategies. In the next section we will start identifying the different waste management challenges and their interconnections, while an in-depth analysis of each of them will be given in separate sections. Focus will be on European scenarios, based on available data and statistics, while the overall proposed concepts and challenges solutions can be extrapolated to other areas such as Asia.

### **Overall identification of agricultural waste management challenges and their interconnection**

The first key challenge to be discussed deals with the environmental and economic challenges of agricultural residue management strategies, in particular in terms of lack of adequate and early prediction tools able to provide clear guidance to policy makers as well as end-users. Life Cycle Assessment (LCA) is a methodology widely used for quantifying the environmental impacts of products and services. Despite its applicability the LCA is associated with certain data limitations (e.g. Avadi et al., 2016), more precisely inventory data for the agricultural residue chain, which are missing in general (i.e. very few agricultural residue chains have been assessed and hence only very few inventory data are available) or not easily accessible (i.e. available inventory data are most often representative for bench or pilot scale). Above all, LCA is most commonly applied for “*a posteriori*” comparative assessments at full scale (i.e. full industrial scale) and the assessment methodology is therefore most often assumed unable to guide cutting edge research and development. Other indirect assessment means for quantification of the environmental burdens associated with new ways of utilising agricultural residues hence need to be considered. Such indirect assessment means are fused metabolic and LCA based approaches as presented for urban areas by Goldstein et al. (2013). Such fused assessment forms can be expanded to cover regions or rather territories yielding fused Territorial Metabolism (TM) LCA or rather TM-LCA. Nevertheless, outputs from LCA and TM, and combination thereof, are multidimensional and require simplification and streamlining in order to provide clear and applicable guidance to relevant stakeholders (including policy makers). This highlights the need for multi-criteria decision-making analysis, facilitating and supporting a truly multi-dimensional and multi-actors approach.

The second challenge relates to the weaknesses of current agricultural residue converting technologies. Anaerobic Digestion (AD) processes offer



**Figure 1.** Example of bio-refinery and cascading technologies applied to agricultural residues through wide range of bio-conversion technologies existing at industrial, pilot or laboratory scale levels.

a consolidated route to convert many agricultural residues into biogas and fertiliser, being the most widespread mature technology for agricultural residue energetic valorisation. Despite this, a number of issues are still unresolved: energy crops instead of local agricultural residues are often used as primary feedstock for AD reactors, also determining an indirect change in land use (Njakou Djomo et al., 2015). Moreover, biogas has a low economic value and AD applicability is poor for lignocellulosic rich waste streams (low conversion yields). Last but not least, the agricultural reuse of anaerobic digestate as potential renewable fertiliser (Bolzonella et al., 2017) can still pose some hygienic and environmental hazards and there can also be storage issues due to the limitation of land disposal imposed by the Nitrates Council Directive 91/676/EEC (EEC, 1991).

Overcoming the bottlenecks for developing innovative building blocks, molecules and materials issued from agricultural residue is the third challenge to face. Nowadays, only a few percentage of chemicals and polymers are bio-based (3% for chemicals according Fiorentino et al. (2017), and about 2% for polymers according to Aeschelmann et al. (2017)) while there is a strong demand to substitute petro-derived chemicals and building blocks with competitive sustainable equivalents. This is needed not only to replace increasing scarce mineral oil as raw material, but also to solve other crucial issues such as widespread plastic waste. The main bottlenecks of agricultural residue recovery and conversion into bio-products and biomaterials are mainly related to energy consumption, degrading processes,

complexity and variability in chemical composition of the waste feedstock, presence of contaminants, and social perception. However, building organic acids, biodegradable plastics or enzymes applications from biomass waste resources create twice as much economic added value as compared to generating electricity, animal feed and fuel applications (Kiran et al., 2015). Bio-refinery and cascading technologies approaches (Figure 1) adapted to agricultural residues still need to be developed.

Another important identified challenge, the fourth one, deals with the integration of agricultural residue business in a circular economy context. In the past, management strategies mainly focused on a single resource for a single final product valorisation. Thereafter, chains have been optimised in terms of product diversification and functionality, energy or water usage (e.g. large scale “port” bio-refinery). Cross-chain valorisation of waste and by-products is challenging due to the heterogeneity of resources, the changes in volumes over time and regions and the variety of conversion and end-uses sectors. By-product streams are mostly bulky and carry significant impact costs. Spatial clustering of different production chains is considered one critical way to make such valorisations feasible. The economic value of a chain’s main product is still driving most business decision making. Moreover, there is a low awareness of valorisation opportunities in alternative sectors (clustered settings) and also with challenging consumers (in-) acceptability of agricultural residue based products. This kind of new distribution of materials, energy and information flows are at the heart of industrial ecology and circular economy strategies. Costs and benefits are not automatically allocated to the same party. Adequate business models are needed to create a setting where all parties involved perceive a “win-win” situation.

Finally, the management of materials and knowledge flows constitutes the fifth challenge to address in order to solve the inappropriate and unbalanced nutrient distribution, contaminants accumulation and agricultural residue conversion issues. In fact, past agriculture developments in many EU-countries has led to environmental, technical and socio-economic issues. Nutrient depletion occurs in soils where exported food and feed are produced, while these nutrients are in excess in livestock breeding regions. In the areas where agricultural residues conversion has been implemented, such as for biogas production, dedicated crops often substitute agricultural residues for economic and supply reasons triggered by agriculture and energy policy measures. Moreover, agricultural residues conversion processes interact with other energy, materials, contaminants and pathogens cycling. Therefore, it is necessary to increase awareness and dialogue of stakeholders across sectors.

In order to address these five challenges, the paper is structured in five related chapters. The need for the development of innovative eco-design



and assessment tools of circular agro-waste management strategies will be first explained. Then, the efficient use of agricultural residues resources will be considered by upgrading the most widespread mature technology (i.e. AD) and by eco-designing innovative bio-processes and products. Finally, why and how to ensure and accelerate the development of new business concepts and stakeholders' platform for cross-chain valorisation of agro-waste on a territorial and seasonal basis will be discussed.

### **Challenge I: Environmental consequences of agricultural residues management strategy: Assessment and early prediction**

Agricultural practices are associated with considerable environmental burdens affecting all environmental compartments, degrading soil, air and water quality, through direct and indirect consumption of scarce resources such as land, water, energy etc.) and much more obviously, through the generation of large and diverse waste streams which are not efficiently utilised.

Soil quality is critical to agriculture, thus being essential to food security in a context of an increasing world population (Hurni et al., 2015). Modern agriculture, and the agro-food industry, are both projecting a multitude of stresses on soils mainly due to production intensification which leads to soil erosion and quality degradation, unbalanced nutrient cycles and organic matter distribution, as well as pollution due to excessive use of chemical fertilisers, pesticides and petro-based products, among others (Zalidis et al., 2002). A serious concern is the unbalanced distribution of organic matter and nutrients irrespective of territorial/soil characteristics and agricultural practices. For instance, in many arable areas, soil nutrients and soil carbon stocks are depleted, inciting intensified use of chemical fertilizers, amounting to 12.5 million tons (Mtons) per year in the European Union alone (Eurostat, 2015). On the contrary, regions with intensive livestock production are characterised by an excess of nutrients and organic matter, mainly caused by the production of manure. Every year, livestock breeding activities yield close to 1500 Mtons of manure, an agricultural residue which can be utilised as fertiliser, in the European Union (EU) (Foged et al., 2011). However, in vulnerable zones with excess manure production (above 170 kg N/ha), farmers are obliged to pay for manure disposal in accordance with the Nitrate Directive (EEC, 1991). Therefore, storage of manure is compulsory and leads to problems associated to degradation thereof (e.g. odours, pathogens and GHG emissions). In fact, livestock and manure production are both in line, impacting on air quality due to the emission of odorous substances (e.g. ammonia), and climate change via GHG emissions accounting alone for 12–17% of total



GHG emissions (approx. 20–30% of which are methane) in EU-27 (Bellarby et al., 2013; Weiss and Leip, 2012).

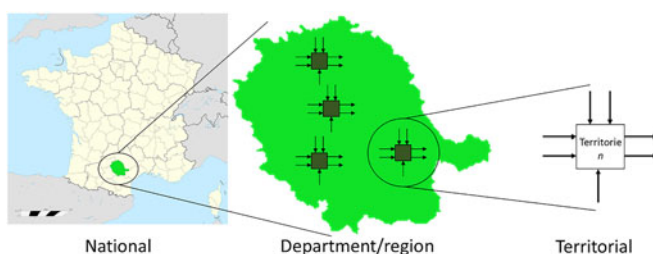
In terms of environmental impacts on water recipients, it is known that agriculture uses about 70% of total global and approx. 36% of European freshwater withdrawals (FAO, 2014; World Bank, 2017) and is further responsible for water quality decrease in the ecosystems. This impact pattern is mainly due to common agricultural practices such as excessive use of fertilisers for attaining high product yields, irrigation practices, use of pesticides and sub-optimised animal farming operations (Zia et al., 2013). All in all, common agricultural practices lead to surface and groundwater contaminations through transport of intentionally applied contaminants (antibiotics, pesticides, nutrients fertilizers, micro- and nano-particles from plastic materials, various bioactive chemical pathogens from livestock manure, waste water sludge etc.) from the arable land surface. Also unintentional water recipient contamination occurs via chemicals and substances ending up on arable land by atmospheric deposition and subsequently following the same emission routes to the aquatic environment as the intentionally applied chemicals.

Anaerobic digestion (AD) has been identified as one of the most efficient and mature technologies to convert agricultural primary residues into bio-energy and bio-based products (e.g. Merlin and Boileau, 2013). Manure, as well as other agricultural residues, can be used as a feedstock for AD in biogas plants, generating a digestate slurry which can be used as bio-fertiliser. Bio-fertilisers can bring back nutrients and organic matter to arable land areas where manure potential is poor, contributing to effective and more sustainable seasonal and territorial fertilising management plans. For example, the extended application of AD to treat manure has been reported to yield an increase in nitrogen availability by 5–20% (Möller and Müller, 2012). AD could also reduce mineral fertiliser demands by around 10%, equivalent to a GHG decrease of 3–5 Mtons CO<sub>2</sub>/year (Möller, Boldrin and Christensen, 2009). In addition, problems relating to excess nitrogen can also be minimised since overall less nitrogen is used in agriculture. Ground water quality preservation can also be improved through the use of AD digestate bio-fertilisers by reducing the contamination from chemical fertilisers (Möller, 2015). Moreover, gaseous emissions are reported to be reduced in general through application of AD for treatment of agricultural residues (e.g. manure) mainly due to the capture and conversion of methane (that otherwise would escape from manure into the atmosphere) and due to the use of biogas to replace fossil fuels (that otherwise would be needed to generate energy) (Möller, 2015). However, due to economic and supply reasons, the cultivation of dedicated energy crops often replaces utilisation of agricultural residues as feedstock in biogas

plants. Dedicated energy crops, and the underutilisation in combination, increases land use for agricultural purposes, emissions of agro-chemicals as well as degradation of the soil quality on arable land (e.g. by production of non-rotatable crops). Considering this degradative development, it is, as e.g. highlighted by Croxatto Vega et al. (2014), crucial to address the whole palette of impacts associated with different agricultural residue management strategies in order to provide clear and valid guidance to end-users (e.g. farmers, industries, policy-makers and other stakeholders).

Of increasing environmental concern is, in addition, the growing use of petro-based plastics in agriculture (e.g. plastic mulch) along with other plastic pollutants (e.g. food packaging), with impacts far from being effectively quantifiable. On top of potentially being capable of inducing impacts in living organism outside arable areas, these plastic pollutants increase soil erosion, reduce water holding capacity, and impact soil biological metabolisms and diversity as well as the organic matter composition and stability of arable soils (Steinmetz et al., 2016). Moreover, leaching of these harmful chemicals into ground water is of particular concern. The presence of micro and nano-plastics in aquatic, terrestrial and marine habitats has been reported (Chae and An, 2017). The potential of these particles to cause harm to human health remains understudied and unquantified. The production and extended use of chemicals (e.g. agro-chemicals) and biodegradable materials (e.g. PHA, lignocellulosic composites), relying on agricultural residue resources, can on the other hand have a significant impact on the substitution of the potentially harmful petro-based plastics in soils (e.g. Costa et al., 2014) and on the micro and nano-particle concentrations in groundwater (Galloway, 2015). The production and consumption of plastic materials in agriculture and in general has rapidly increased since the 1970s. Degradation of conventional petro-based plastics in the environment is estimated to range from 50 up to hundreds or even thousands of years (Zalasiewicz et al., 2016), indicating that conventional environmental impact assessment methods are insufficient to address micro and nano-particle contamination issues, since these methods do not take into account long (i.e. century long) term effects such as those induced by plastic micro and nano particles.

LCA, is a standardised assessment methodology (ISO 14040, 2006) widely used for assessing the environmental impact potentials and trade-offs associated with all stages of a product, process, or service life cycle (ideally from *cradle-to-grave*). The calculation procedure of an LCA consists of 3 steps: (i) compiling an inventory of relevant energy and material inputs and environmental releases; (ii) quantifying the potential environmental impacts associated with identified inputs and releases; (iii) and interpreting the results to help decision-makers make a more informed decision. Weaknesses pointed out in the LCA methodology mainly centres around



**Figure 2.** Illustration of application of TM-LCA applied for assessment of wine regions. Scaling concept from national to departmental or regional allowing for a process-based aggregation of individual producers (territories), shown in theoretical form for the Tarn department in France. Based on Sohn, Croxatto Vega, and Birkved (2018).

the inventory phase due to the vast data demands. Most frequently, inventories are based on, often criticised, large highly aggregated and often non transparent databases. Even when local processes are involved assessors are often forced to use general inventories most often representative for generic regions (e.g. Europe, World) and hence most likely representative for a different technological context than the one actually being assessed. More importantly, although not often discussed, LCA is most often applied as “*a posteriori*” assessment at fully upscale stages and is therefore only rarely used in early stages of R&D, hence with almost no possibility of feedback and consequently no guidance for eco-design. This was identified and discussed by Hospido et al. (2010), but no concrete attempts to operationalise it was presented. However recent developments in the application of LCA for early stage decision support regarding bio-refining has emerged by combination of LCA and Process Flowsheet Simulation, as presented by Corona et al. (2018). The approach presented by Corona and co-workers is however still in its infancy and needs further validation, especially for application in agricultural residue utilisation. Furthermore, the LCA method does not take into account long term impacts such as those related to plastic pollution. Some research has been performed in assessing and comparing the environmental performance of different manure management strategies in the field of LCA, including anaerobic digestion (Croxatto Vega et al., 2014) but in general only a limited number of LCA studies have addressed novel products from agricultural residues (Al-Oqla et al., 2014).

Another potential methodology for assessing the implications of altered agricultural residue utilisations is Territorial Metabolism (TM), which, being a regional scale version of urban metabolism (UM) (Wolman, 1965; Kennedy, Cuddihy and Engel-Yan, 2007), quantifies the material and energy flows across a certain geographic region at e.g. regional scale. Such territories can be specific agricultural regions with a distinct palette of products (e.g. wine regions such as Roussillon-Languedoc), which, contrary

to cities, may exist as a patchwork of e.g. wine producers producing a specific grape variety (Figure 2). As already illustrated by Goldstein et al. (2013) the material flow and energy analyses at urban scale and hence also at a regional scale have a range of limitations mainly caused by the incomparability of material flows (e.g. concrete and steel) and hence the lack of valid proportionality (Laurent, Olsen, and Hauschild, 2010) between urban/regional flows and resulting environmental impacts.

Fusing TM and LCA has been initiated on urban areas (UM-LCA from Goldstein et al., 2013; Ipsen et al., 2018; Ohms et al., 2018,) and offers a convenient and powerful means for systemic assessment of the relative environmental implications of introducing new waste management schemes at territorial scale (Sohn et al., 2018). Unlike territorial LCA (related to LCA applied to a territory, Loiseau et al., 2013, 2018, Mazzi et al. 2017), hybridizing TM with LCA deals with performing LCA on the metabolism (i.e. changes in the metabolism induced by a given technology) of a territory. LCA fused metabolic assessments of specific geographic areas can generally solve the material flow assessment from issues encountered in “pure” UM and TM, by converting material flows into standardised (and hence comparable) sets of environmental impact indicators at various aggregation levels (e.g. mid-point, end-point and single score). TM-LCA hence will also offer an alternative and indirect way of assessing new utilisations of agricultural residues by enabling environmental performance assessment at regional scale before and after introduction of an agricultural residue utilisation technology (Sohn et al., 2018). The fused TM-LCA approach and its ability to deliver a thorough and systemic picture of the environmental performance potential of a given region or regional sub-systems, such as specific agricultural residue systems, allows for optimal agricultural residue management strategies at appropriate (regional) scale and complexity levels (Sohn et al., 2018). Considering that outputs from TM-LCA require specific competences to be properly applied, these results need to be streamlined in order to provide clear guidance to different end-users. The development of cross-disciplinary and multi-criteria evaluation and decision support tools provides a suitable platform for discussions among stakeholders, bringing in structure and knowledge for use in complex decision situations like those related with the policy making on agricultural residue utilisation (Sohn et al., 2017). The integrated TM-LCA multi-criteria approach could also become useful for the simulation and prediction of the environmental performance of future systems, by further extending the approach with scenario analyses, making it possible to include regional and seasonal aspects, various potential product life cycles (and hence trade-offs) and compare these across a broad range of impacts indicators simultaneously, including undesirable contaminants in circular management. The

application of these assessment and interpretation methodologies to the early stages of new residual resource management can foster innovation addressing all three sustainability pillars (Economic, Environmental and Social) coherently and enable research to focus on hot/critical points for eco-design. By upgrading and improving existing methodological frameworks to streamlined integrated strategic environmental assessment (multi-criteria evaluation model supported by geographic information system application), the decision making process within the agricultural residue management planning is expected to be significantly facilitated and improved.

### **Challenge II: Converting agricultural residues into biogas and bio-fertiliser: Required upgrading technologies**

Anaerobic Digestion (AD) is generally considered the most mature and widespread agricultural residue conversion technology. According to the European Biogas Association (EBA, 2018), there are currently around 17,500 AD plants running in Europe, most of which are farm-based, with a total installed capacity of 9.98 GWe while the total amount of electricity produced from biogas is estimated in more than 65 TWh. As for biomethane generation there are more than 500 plants in operation in Europe, with a production capacity equivalent to 17,264 GWh.

Despite being so robust, this technology still presents several technological limitations and weaknesses, namely due to low conversion yields of organic material rich in lignin (Ahiring et al., 2015), low economic value as well as issues related to feedstock supply and digestate handling and storage.

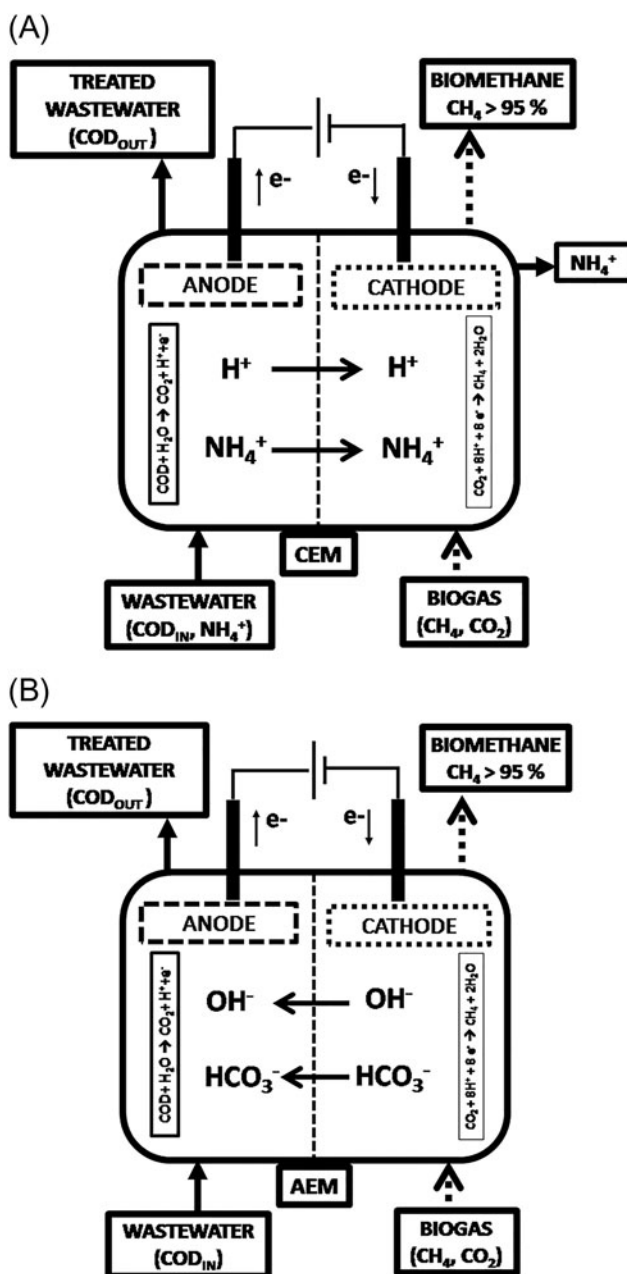
AD recovery yield can vary widely depending on feedstock and operational conditions applied (Möller, 2015). For example, the use of lignocellulosic-rich waste streams for AD has not been widely adopted due to the recalcitrant nature of complex plant cell walls, which makes them resistant to microbial attack, resulting in low biogas conversion yields. This has been subject of increasing research investigating numerous different techniques such as mechanical, chemical, thermal and biological processes (e.g. Hendriks & Zeeman, 2009; Zheng et al., 2014; Carrere et al., 2016; Paudel et al., 2017). However, the key issue is on assessing the real benefit of pre-treatment in real conditions. Very often, in fact, the capital and operational costs for pre-treatments are greater than the effective return in terms of produced biogas (Budde et al., 2016). Mechanical pretreatments (such as grinding and milling or ultrasound) have high energy requirements if compared to their impact on methane yields (Dumas et al., 2015; Barakat et al., 2013; Bundhoo and Mohee, 2018). Chemical treatments (e.g. acid or alkali) are low energy but high hazardous chemicals consuming with the risk of chemical contamination and formation of inhibitors (e.g. furans and

phenolics) (Alizadeh et al., 2005; Sambusiti et al., 2013; Carrere et al., 2016). Except for ozone pretreatment which is described as effective at lab scale for lignin breakdown and methane yield increase without toxic compounds risk, but rise concerns about economic and environmental viability (Domański et al., 2017). Hydro-thermal and steam explosion significantly increase biogas production which compensates their high energy demand (Carrere et al., 2016). Wet explosion is a promising technology for lignocellulosic pretreatment, which combines steam explosion with oxygen addition (thermo-chemical method). This technique can be adjusted for different biomass feedstock and has been successfully applied to AD processes using agricultural residues as well as manure fibres (Ahrling et al., 2015). Selective enzymatic treatments of agricultural residue have been reported to enhance co-digestion of straw and manure at low energetic cost (Wang et al., 2016). Rouches et al. (2016) reported a significant increase in methane production from wheat straw pretreated with white-rot fungi, despite of some organic matter losses. Biological pre-treatments are therefore interesting alternatives to be further assessed for their benefit/cost balance.

According to EBA data (EBA, 2018) on electric energy and biomethane production, the global actual biogas production in Europe is around 35 billion  $\text{m}^3$  per year. The implementation of innovative and effective pre-treatments, isolated and/or combined, expanding the range of potential feedstock can make the sector even more robust, and biogas production could be increased by 20-30% (Paudel et al., 2017) equivalent to 7 to 10.5 billion  $\text{m}^3$  biogas per year. If we consider to substituting the energy produced from coal, which determines an emission of 0.94  $\text{kgCO}_2\text{-eq}$  per kWh produced, with this renewable energy source we can expect a net reduction in  $\text{CO}_2$  emissions in the range of 15–22 million  $\text{tonCO}_2\text{-eq}$  per year.

Another important point to consider is that biogas presents low economic value due to its high  $\text{CO}_2$  content (35–50%) which decreases energy content and limits direct uses to heat production or co-generation. Upgrading of biogas (50–65%  $\text{CH}_4$ ) to biomethane (>90%  $\text{CH}_4$ ) is usually carried out by adsorption or scrubbing processes, in order to remove  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , water and other minor contaminants, which are costly and energy-demanding (Khan et al., 2017; Angelidaki et al., 2018). The resulting purified biomethane can thereafter be used for direct natural gas grid injection as well as for the automotive sector in conventional natural gas vehicles, with significant reduction of hydrocarbons, nitrous oxide and other GHG emissions and overall improvement in the combustion qualities of methane.

Microbial electrolysis cells (MEC) is an emerging eco-efficient and low-cost technology which can generate biomethane or hydrogen from organic material by applying an external electric potential or a current. In a MEC,



**Figure 3.** Microbial Electrolysis Cell (MEC) aimed at wastewater oxidation and biogas upgrading equipped with a cation exchange membrane (A) and anion exchange membrane (B).

“electro-active” microorganisms, or electro-trophes, are attached to the anode and oxidise organic waste substrates to carbon dioxide by using the electrodic material (usually graphite based) as final electron acceptor of their metabolism. The electrons produced by the anodic oxidation reaction, flowing across the external circuit, are used to (bio)catalyse the production



of reduced target molecules such as  $H_2$ ,  $CH_3COOH$  or  $CH_4$  (Zhen et al., 2017; Zeppilli et al., 2016a). This enables coupling waste treatment with the generation of energy carriers and chemicals. If a MEC is configured for “electromethanogenesis”, i.e. for reduction of  $CO_2$  to  $CH_4$  catalysed by electro-trophes attached to the cathode, the wastewater treatment (COD) oxidation in the anode can be coupled with the biogas upgrading to biomethane (Figure 3) (Villano et al., 2013; Blasco-Gómez et al., 2017).

The implementation of MEC can decrease the energy demand for biogas refining and increase the overall energy efficiency of biomethane production compared to currently used technologies such as water scrubbing and pressure swing adsorption (Andriani et al., 2014). Moreover, by using a MEC, an additional  $CO_2$  removal mechanism occurs due to the alkalinity generation in the cathodic chamber (Xu, Wang and Holmes, 2014) which promotes  $CO_2$  sorption as  $HCO_3^-$ . Thanks to this mechanism, by using a methane producing biocathode, a maximum yield of 9 moles of  $CO_2$  per mole of  $CH_4$  produced can be obtained (Zeppilli et al., 2016b). By considering the latter mechanism, a reduction of the estimated energy consumption of almost one order of magnitude can be supposed for the electromethanogenesis process.

Another interesting and alternative approach is the use of two-phase AD processes, which comprise a fermentation step (with production of biological  $H_2$ ) followed by a methanisation process, resulting in a biogas enriched in  $H_2$  (up to 10–20%) (Micolucci et al., 2014). The use of two-phase AD processes increase conversion yields up to 37% (Premier et al., 2013) and allow the concurrent production of bio-hythane (Monlau et al., 2013). Bio-hythane (hydrogen enriched methane) enables a reduction of HC, NO<sub>x</sub> and GHG emissions, improved combustion qualities (higher engine power performances) and can be directly used in conventional natural gas vehicles. Although hythane<sup>®</sup> fuel is already used in several countries worldwide (USA, India), hythane<sup>®</sup> production at an industrial scale is only achieved by catalytic methods with high energy requirements. A competitive value of 1.5 €/kg of hydrogen (yield 10 moles  $H_2$ /mole of glucose, feedstock below 0.05 €/kg) could be targeted with this technology (Bolzonella et al., 2018).

An attractive integration of a two-phase anaerobic digestion AD process and MEC technology have been investigated recently (Zeppilli et al., 2017); the results showed the possibility to use a mixture of the effluents from the first (acidogenic fermentate) and the second stage (digestate) of a pilot scale two-phase AD to sustain the MEC process.

Furthermore, two stage AD generates volatile fatty acids (VFAs) rich residual effluents (Cavinato et al., 2017) which are promising precursor for further conversion to bio-based chemicals such as polyhydroxyalkanoates

(PHAs) and derivatives (Reis et al., 2011), which have numerous potential uses as speciality biopolymers for packaging applications (Chen, 2009).

Indeed, PHAs has been identified as a promising potential of the bio-waste bio-refinery (Bugnicourt et al., 2014), especially because: (i) its production process has the best potential to cope with large heterogeneity of the waste feedstock, in particular because the first production step, i.e. the acidogenic fermentation, is both robust and flexible and provides stable feedstock to the PHA production; (ii) PHA includes a whole family of copolymers with a wide range of tunable properties, so that PHA can be the main constituent of several bioplastics and their biocomposites, with a wide portfolio of applications (Chen, 2010); (iii) PHA is bio-based not only because it is produced from organic biomass, but also because it is produced through a process, which is mostly biological under mild conditions (e.g. no sterile conditions are required); (iv) in comparison with other biological processes, the PHA-producing process does not produce an excess of sludge that needs to be handled, as the polymer makes up to 70% of the biomass (Reis et al., 2011).

International market of PHAs was estimated at 50,000 tons in 2017, representing 2.4% of the total bioplastic production (2.05 Mtons), with an expected increased production in 2020 (European Bioplastics, 2017). PHA polymers are commercially available at a price ranging between 5–8 €/kg. By combining the use of agriculture residue as the feedstock and the integration of a mixed-culture PHA process into an AD-based technology chain, PHA costs could be reduced significantly with respect to PHA benchmark glucose fermentation and axenic-culture processes (Choi and Lee, 1999; Kim, 2000; Reis et al., 2011; Fava et al., 2015). Additionally, GHG saving can be increased by extending the valorisation of the residual CO<sub>2</sub> streams from innovative AD technologies into CO<sub>2</sub> consuming technologies, such as microalgae-based products (Posadas et al., 2017).

On the other hand, AD digestate, a nutrient rich fertiliser, is able to lessen the environmental concerns of animal husbandry (Battini et al., 2014) and produce renewable fertilisers (Bolzonella et al., 2017), but still raises concerns about possible hygienic (e.g. pathogens), environmental (e.g. antibiotics, metals) hazards and storage (e.g. degradation, odours and GHG emission) issues (Scaglia, Pognani and Adani, 2015), while storage is necessary because of the land disposal limitation imposed by EU nitrogen regulation (EEC, 1991).

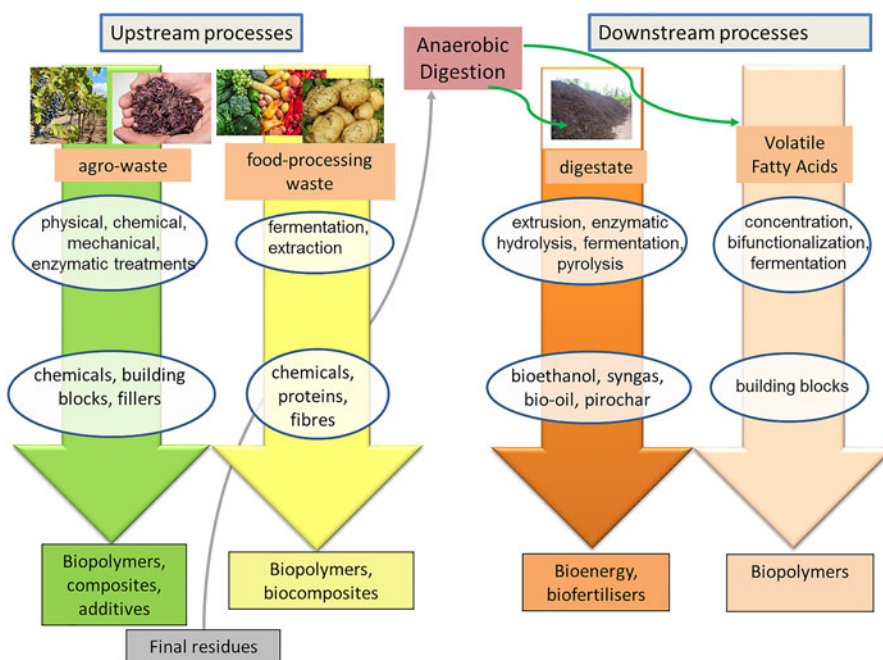
The integration of AD with pyrolysis processes has been proposed, namely for lignocellulosic materials (Hübner and Mumme, 2015; Fabbri and Torri, 2016; Feng and Lin, 2017). Pyrolysis of solid AD digestate can extract additional energy from this residual material, by conversion into syngas, bio-oil and biochar fractions, which can be further used for

electricity generation. According to Monlau et al. (2015) this kind of system can provide a 42% increase in the production of electricity compared to stand-alone AD plants. The resulting biochar can also be used for soil amendment, and carbon sequestration (Fabbri and Torri, 2016; Feng and Lin, 2017). Overall due to all gains compared to the use of conventional petrochemical products (energy, fertiliser etc.), an AD-pyrolysis dual system could save 2905 Gton CO<sub>2</sub> eq/year (Monlau et al., 2015).

In addition to all these technological bottlenecks that have been discussed, it is essential to assure an optimal exploitation of agricultural residue sources and AD products (nutrient and energy), which can be attained by taking care of geographical/seasonal waste distribution, end-uses and soil requirements. Simultaneously new emerging technological options (e.g. MEC, 2 stage AD) should be considered for their potentials and ability to be integrated into existing AD plants at different scales. Eco-efficient and flexible (adaptable to local and seasonal waste streams) AD plants using alternative and efficient technologies should be largely implemented to convert 75% of manure and reduce their impact on GHG emission (30%) by lowering methane and nitrous oxide emissions, both otherwise released after application of manure in the field (Battini et al., 2014). The establishment of advanced chemical and biotechnological biogas-based platforms, with a set of novel products (e.g. biofuels, biomaterials) can have significant impact in terms of increased opportunities for the valorisation of agricultural residues. In particular, biogas production could increase by 10–20% from the actual 47,000 GWh per year (EBA, 2018) due to a combination of factors like the pre-treatment of lignocellulosic feedstock and the wider implementation of two-phase thermophilic processes.

### **Challenge III: Converting agricultural residues into innovative building blocks, molecules and materials: Overcoming key bottlenecks**

The potential opportunities for developing bio-products from agricultural residues are known to be large, but, from a technological point of view, biomass conversion processes need improvements and a more in-depth knowledge about their potentialities as well as an environmental, economic and societal sustainability. The petro-chemical industry exploits mature technologies and still provides the most universally used chemicals, multi-purpose plastic materials and energy in the global economy despite severe growing concerns about environmental impacts (e.g. global warming, 7<sup>th</sup> plastic continent). From a chemical and biotechnological perspective, nearly all chemicals and building blocks for plastics can be made using renewable raw materials. However not all the processes are commercially feasible and



**Figure 4.** Cascading activities around anaerobic digestion (upstream and downstream processes) to valorise agro and food processing waste.

efficient. Furthermore, products often display insufficient purity or are too expensive (Harmsen, Hackmann and Bos, 2014).

Presently, only a few percentages of chemicals are bio-based (Fiorentino et al., 2017; Aeschelmann et al., 2017) while platform chemicals are the main feedstock for producing secondary chemicals, chemical intermediates and final products (Jang et al., 2012).

Biological production of platform chemicals from agro-resources, bio-mass waste and food processing residues has been reported in the literature (Pfaltzgraff et al., 2013; Sheldon, 2014; Lin et al., 2013; Dugmore et al., 2017; Fritsch et al., 2017). However, valorisation techniques have only been validated at lab-scale. Further optimisation and method integration studies need to be carried out. It is thus essential to develop breakthrough technologies in agricultural residue conversion and bio-refinery, in order to increase opportunities for valorisation of waste, by-and co-products, promoting environmental and economic benefits for the farming sector (e.g. development of new products and processes).

The development of an agricultural residue based bio-refinery strategy passes through stepping up research in breakthrough residue conversion into value added chemicals and materials. Knowledge of agricultural residue molecular structure and characteristics should be enhanced. Advanced selective extraction and conversion processes (e.g. enzymatic, supercritical

fluid extraction, depolymerisation) should be consequently developed. This allows to recover bioactive molecules (e.g. polyphenols, hydroxy acids, proteins) that could be used as building blocks for polymers or platform molecules for fine chemicals, which, in general, create more than twice added value compared to generating electricity, animal feed and fuel applications (Kiran et al., 2015).

Moreover, in order to develop a bio-refinery concept starting from agro-waste and by-products, another challenge is to move towards a zero-waste economy. This can be achieved through the development of valorisation cascading activities around the anaerobic digestion process, which is already available at the industrial scale. This means that upstream and downstream processes with respect to anaerobic digestion can allow the full valorisation of wastes, as represented in a schematic way in Figure 4.

As an example, chemical, enzymatic or physical processes can be investigated and optimised in such a way to recover functional molecules with antioxidant and antimicrobial properties, such as polyphenols from red and white wine pomaces. These molecules can be exploited as green additives in polymeric systems to impart specific properties to the matrix (Kirschweg et al., 2017). They can potentially substitute controversial plastic additives such as antimicrobial silver nano-particles and nanoclays, which represents a huge market of \$16.17 billion by 2020 with a CAGR of 8.7%, currently led by BASF, Bayer, Dow Chemical and Clariant (Markets and Markets, 2015). The global polyphenols market is expected to reach 33.88 kilo tons by 2024, growing at a CAGR of 8.4% from 2016 to 2024, according to the report of Grand View Research, Inc. (Grand View Research 2016).

Furthermore, it is notable that agricultural residues and, in particular, aromatic lignin derivatives, can be a source of aromatic compounds that could be further used as building blocks for the synthesis of polymers to substitute traditional polyesters, such as petro-derived PET (Polyethylene terephthalate) (Pion, Ducrot and Allais, 2014; Mialon, Pemba and Miller, 2010; Gioia et al., 2016; van Es, 2013).

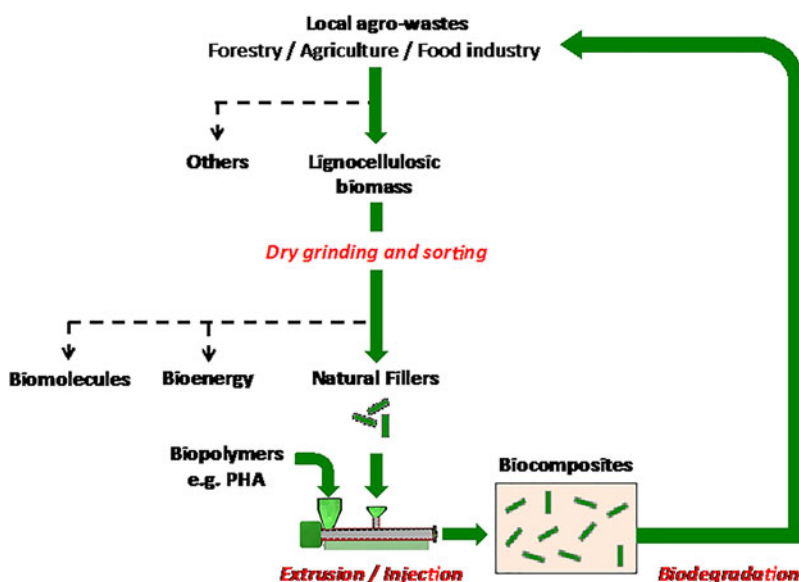
Bisphenol A is a chemical compound massively used since the 1960s in the production of synthetic polymers, such as polycarbonate plastics and epoxy resins, with widespread distribution in everyday use products (e.g. packaging, bottles) (Michałowicz, 2014). There is today evidence of Bisphenol A widespread migration and accumulation in the environment, as well as in food and drinking water, and even in human tissues and fluids, with associated significant toxicity effects (Michałowicz, 2014). Exploring the substitution of Bisphenol A, and other petro-based monomers, by aromatic building blocks from biological sources, such as phenols, is a large innovative opportunity for application in the polymers and

plastics sector (e.g. 28 Mtons epoxy resins market). The generic depolymerisation pathway of lignin can be applied to a wide range of biomass types, namely vine residues (Deepa and Dhepe, 2015). Thanks to the large structural diversity of natural polyphenols, the exploitation of (poly)phenols as aromatic substitutes offers different possibilities of selection and fine tuning in specific applications, which are not available for monostructural chemicals such as Bisphenol A. This diversity can avoid the accumulation of a universal molecular species such as Bisphenol A in the environment, lowering the associated risk (Aouf et al., 2014).

As regards bioplastics, they currently represent about one percent of the approx. 320 million tonnes of plastic produced annually, with only the half being bio-sourced (European Bioplastics, 2017). But as demand is rising and with more sophisticated biopolymers, applications, and products emerging, the market is continuously growing. According to the latest market data compiled by European Bioplastics and Nova-Institute (European Bioplastics, 2017), global bioplastics production capacity is set to increase from around 2.05 million tonnes in 2017 to approximately 2.44 million tonnes in 2022. The applications are multiple, from rigid packaging to horticulture and agriculture, with a high number of manufacturers, converters and end-users in Europe. As an example, the United States Flexible Packaging Association (FPA, 2017) reported that 62% of consumer products goods companies expect to change their packaging within the next year with sustainability being a key consideration and 90% of the packagers say that sustainable design has become a key consideration in packaging-design decisions. Biodegradable polymers lighten the environmental concerns of petro-based plastics use and may be recovered in the form of compost and/or energy (e.g. through AD). Moreover, developing bio-based products (e.g. bioplastics) from agro-waste can provide GHG savings from at least 55% compared to the equivalent EU's fossil products (Eerhart, Faaij and Patel, 2012). The European market of polymers accounts for 60,000 companies, 1.5 million jobs, production of 60 Mtons, and combined turnover of close to 340 billion euro (PlasticsEurope, 2017). It could be using 80% agricultural residues resources, before re-entering the nutrient cycle, for providing safe and eco-friendly materials and chemicals for packaging, building and construction, automotive, agriculture and others.

Therefore, new agricultural residue based biopolymers should be developed to facilitate the growth of the bioplastics sector regarding advanced technical properties, cost reduction, high consumer acceptance and boosting climate change mitigation. Replacing 50% of petrochemical polymers consumed in Europe by alternative bio-polymers issued from agricultural residues, would mean to consume less than 30% of agricultural residues potential (calculations made using data from PlasticsEurope (2017) and Elbersen et al. (2012)).





**Figure 5.** Up-cycling of lignocellulosic wastes for the production of biocomposites.

Polyhydroxyalkanoates (PHAs) are a group of renewable and biodegradable bio-based polymers (polyesters), produced naturally by bacteria. These are starting to gradually substitute conventional plastics (e.g. polypropylene, low-density polyethylene) presenting similar physicochemical, thermal, and mechanical properties (Kourmentza et al., 2017). Some small scale-units are operating in Europe, but the main PHA production unit is located in China (Tianan company), using maize as feedstock. This brings some sustainability issues, namely in terms of competition with food use, water footprint and economic cost. Therefore, it is important to explore the use of sustainable feedstock for fermentative PHA bioreactors. The production of PHA from waste materials such as sugar molasses (Carvalho et al., 2014), olive oil mill wastewater (Hilliou, Machado, et al., 2016) or cheese whey (Hilliou, Teixeira, et al., 2016), has been successfully tested. Furthermore, VFAs, such as acetate and butyrate, have been described as efficient feedstock for PHA production by photosynthetic mixed cultures (Fradinho, Oehmen and Reis, 2014). Therefore, VFA-rich residue streams from two step AD could be purified and functionalised into bi-functional monomers for bio-polymers or further converted into biodegradable PHAs by innovative photo-fermentation processes (Fradinho, Oehmen and Reis, 2014). The latter can offer the advantage of saving energy (because no aeration is required) and has the potential for further decrease PHA cost (see previous section, Challenge II).

One strategy to modulate PHA properties while maintaining the full biodegradability of the materials and reducing the final cost of materials is to mix it with low-cost lignocellulosic fibres. The cheapest and most



environmentally virtuous lignocellulosic fibres are those obtained from agriculture and food industry solid by-products – their up-cycling as fillers in biocomposites would also help waste reduction (Berthet et al., 2015, 2017) (Figure 5).

Reinforcing fillers can be easily produced by dry fractionation of a given lignocellulosic biomass, by combining dry grinding and sorting processes (Berthet et al., 2017; Lammi et al., 2018). Dry fractionation enables to avoid the consumption of water or chemicals and therefore generates very little waste (Lammi et al., 2018). Moreover, fibres can be present also in the final solid residue obtained after extraction processes of high-value bio-active molecules, such as polyphenols, from agro or food processing by-products. Also this fibrous residue can find a final exploitation in reinforcing polymeric materials (Totaro et al., 2018). Biocomposites from lignocellulosic residues appear as innovative and promising materials for many sectors, including horticulture, building, automotive and packaging, provided that the presence of prohibitive contaminants can be discarded (Berthet et al., 2016).

Finally, the most significant building blocks derived from sugars for polymer production have been listed as followed (White et al., 2004): 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol. Among these top twelve promising platform chemicals, succinic acid (SA) has emerged as one of the most competitive bio-based chemicals (White et al., 2004; Weastra, 2013) due to its ability to form the basis for many high-value replacement products, including phthalic anhydride, adipic acid, and maleic anhydride. In fact, one of the major driver for the growth of this market is represented by the increasing applications of SA, including industrial applications (57%), pharmaceuticals (16%), food & beverages (13%), and others (14%) (Sisti et al., 2016). Traditionally, SA is produced from petroleum via oxidation of *n*-butane but it can be obtained from biomass sugar fermentation (Lin et al., 2012). While petrochemical production has remained stable for years, the global bio based succinic acid market is expected to reach market volume of 710.0 kilo tons by 2020, growing at a CAGR of 45.6% during 2013-2020 (Allied Market Research, 2014). According to Weastra (2013) market study it is expected that bio-based succinic acid will be more cost-effective than petro-based one in the future. Recent advances in fermentation from different glucose sources (e.g. corn wastes) and in purification technologies succeeded in making bio-based SA economically attractive (Sisti et al., 2016).

Demonstration bio-SA plants have been built in North America, Europe and Asia Pacific by leading companies (BioAmber, Reverdia, Myriant and BASF), but the global market share of bio-SA is still very low. Innovative

strategies should be developed to decrease bio-based SA raw materials and production cost in order to get closer to the 3.0 €/kg product value of bio-SA specified by PEP (Process Economics Program) (Vaswani, 2010) at the best case design capacity. SA issued from agro-wastes could replace many petro-based chemicals, resulting in a large reduction in pollution, namely 94% decrease in GHG emissions (Lin et al., 2013). SA fermentation is traditionally conducted in batch using pure substrates and there is a lack of studies on mixed agro-waste for SA fermentation and on engineered strains able to metabolise carbohydrate rich agro-waste (Kiran et al., 2015). The use of metabolic and evolutionary engineered yeast, can contribute to improve yield and concentration, limit by-products and to adapt strains to diverse carbon sources and inhibitors from agro-wastes.

#### **Challenge IV: Promoting agriculture residue business in a circular bio-economy context**

The concept of industrial ecology in eco-industrial parks was introduced in the 1990s by amongst others Frosch and Gallopoulos (1989). In such system “*Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry in the environment*”. An eco-industrial park is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resources issues, including energy, water and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would have realised if it optimised its individual interests (Lowe, Moren and Holmes, 1996). Currently, the notion of an eco-industrial park addresses inter-company collaborations aimed at optimising resource efficiency, more commonly called industrial symbiosis. The most famous example is “Kalundborg” in Denmark (<http://www.symbiosis.dk/en>). Few studies highlight key success factors and barriers to the implementation of existing eco-industrial parks around the world (Massard, Jacquat and Zürcher, 2014). But the implementation of Industrial Ecology conceptions is still difficult because it requires a new vision of customer-supplier relationships, new forms of organisation and new business models, often at the crossroads of various value chains.

Most eco-industrial parks are petrochemical, chemical, or diverse industries but there are few actual projects and studies that rely on cross chain valorisation of agriculture residues. Among the completed projects, there is for instance one agro-industrial ecosystem in France (Bazancourt-Pomacle Biorefinery, see Schieb et al., 2015) and a state-owned conglomerate operating China’s largest sugar refinery with over 3,800 workers and 14,700 ha

land to cultivate and utilise all sugar cane by-products since more than four decades ago (Guitang Group, see Shi and Chertow, 2017).

However, the agro-food sector is not fully integrated in the bio-economy landscape yet. Efforts in R&D, business modelling and framework conditions are needed to favour such integration and permit a complete conversion, similar to a petro-chemical refinery, of the full fresh weight of harvested crops (food plus agriculture residue mass) into food/feed, bio-energy and bio-products, in order to increase the potential of agricultural biomass without pressure on land uses and plant productivity. For effective use of agricultural resources, including agriculture residue, with better allocation of environmental benefit and added value, it is required to bridge the gap between innovative agriculture residues upgrading technologies and business opportunities by developing a cross-sectorial vision able to review the entire value of the agriculture residue chain.

A targeted analysis of existing eco-innovative business models, as well as a strong business model generation methodology, can enable the development of a few business model options, for each case study cross sectorial value chains. This can also allow to highlight and mitigate key barriers that need to be raised through the evolution of the framework conditions (new policies, incentives) or through a marketing and communication strategy to show all the benefits and raise market acceptance. Scientific evidence from technological and scientific achievements, including territorial approach will substantiate which options profit from local or regional proximity, and fit in locally designed agro-parks promoting the bio-economy and the industrial symbiosis in food, feed, energy and bio-products sectors. An improved knowledge on agriculture residue molecular complexity and heterogeneity and optimal streams (mostly organic and also conventional) management can permit to diversify the feedstock used for generating energy (e.g. biogas), materials and commodities such as agro-chemicals, polymers and other materials. Innovative locally adaptable strategies based on developing agriculture residue conversion into biogas and bio-products, or intermediate chemical building blocks, should be implemented at full-size scale and their associated knowledge transferred across levels. This approach can contribute to doubling biogas production by 2020 to reach the 1.5% of the European Union's primary energy supply and the 5% of its overall natural gas consumption according to the National Renewable Energy Action Plans (European Commission, 2018). It can also contribute to reaching the 2030 EU targets in the waste area, namely net savings for EU businesses of €600 billion, increasing resource productivity by 30%, boosting GDP by nearly 1%, and creating 2 million additional jobs. A favourable European and national policy and legislation context on waste should support circular economy by setting clear objectives and supporting

business eco efficiency activities (industrial symbiosis including materials, water, energy, and heat symbiosis).

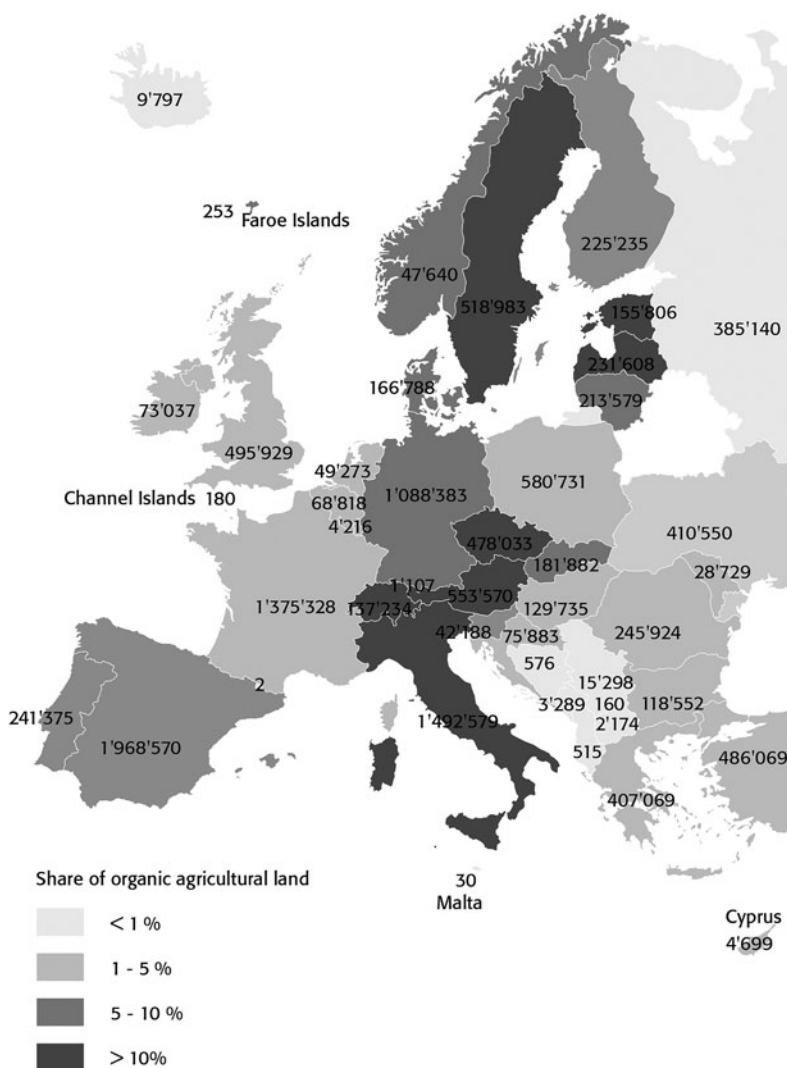
### **Challenge V: Connecting stakeholders and sharing knowledge about agriculture residue management**

Elapsed agriculture development in many EU-countries has led to environmental and socio-economic issues that are amplified at specific region/supply chain nexus. As referred to previously (Challenge I), while there is incidence of soil nutrient depletion in arable areas without livestock, excess of nutrients, odorous substances, methane emissions and pathogens transmission issues occur in livestock breeding regions. On the other hand, in urban regions large amounts of food are imported and there are significant negative ecological impacts of organic nutrient load from wastewater and sewage sludge (Buckwell, Heissenhuber and Blum, 2014). Although some agriculture residue conversion processes have been implemented, their development is hampered because most of them are currently not properly addressing territorial environmental and economic ambitions. Dedicated crops often substitute agriculture residue sourcing for economic and supply reasons, for example fodder maize used as feedstock for biogas is taking a large share of the biomass cropping area in Germany. To deal with these constraints it is necessary to address efforts in order to increase the awareness and dialogue of stakeholders across sectors.

Stakeholders are well organised at the production stage and at national and also at European levels namely through winery, livestock or cereal producers, and farmers' associations. However, smart agriculture residue chains clearly require further cross-sector dialogue and the addition of other actors (e.g. converters, end-users, waste management, Civil Society Organizations (CSO) representatives, knowledge providers, regional and national policy makers, etc. to properly tackle sustainability challenges and market opportunities, both in terms of resources and end-products, according to the possible territorial scales depending on several factors such as geographical, political or historical constraints. On the other hand, agriculture residues valorisation interacts with a number of other systems such as the energy system and raw material production or contaminants accumulation and pathogens cycling (Möller, 2015). In this context, spatial data infrastructures and databases on agriculture residues are needed for territorial and socio-economic land planning policies and optimal use of resources, taking into account the INSPIRE Directive 2007/2/EC (European Commission, 2007a) as an umbrella resource. Such information are needed for multi-criteria evaluation method, decision making process and agro-waste management strategies, e.g. GIS technology is used to support

the spatial/territorial analysis: wastes production streams, collection, transport facilities, treatment plants availabilities, specific soil needs and water quality issues, substitutable products flow, population and economic growth and job creation etc. (Josimovic et al., 2015). For example, biogas production makes much sense when both electricity and heat can be used via block power stations (co-generation). Heat can at best be sold through long-distance heating for private households or industry, or through district heating systems. Most agricultural residues are available only far from urban regions, and especially husbandry farms are, on purpose, built in some distance of private dwellings in order to avoid noise and smell disturbance. Consequently, the biogas-generated heat is difficult to valorise, except when the process heat is used for drying agriculture products locally.

The concept of territorial “cyclifiers” i.e. stakeholders and materials stream connectors developed through the creation of joint stakeholders’ platforms and other joint structures (on the availability, needs and options for smart use of agriculture residue) is thus essential to tackle this challenge. While taking into account regional/territorial divisions with defined agronomical, ecological and economic situations of agriculture residue management, it is necessary to increase awareness on the need to reduce and exploit agriculture waste and of the potential pathways for their reduction and recovery. This could enable an integrated and synergistic use of biomass components from various types of agriculture residual resources to achieve high performance end-use products. A shared knowledge about market, supply chains, valorisation and marketing of agriculture residue could also be assured through high synergetic interlinkages and interconnections between stakeholders in different domains and levels with better information flow and management, taking into account, of course, the necessary feedback of assets into agricultural cycles. A multi-stakeholder approach includes the practical users, policy makers, knowledge providers and researchers and other stakeholders throughout the whole process of research and development to improve the findings’ applicability for valorisation of agricultural residue and enhance their exploitation (Durham et al., 2014). The multi-stakeholder platform can act like a consultation body made of different concerned parties who perceive the same problem (in this case agricultural residues management and usage problem), who realise that it is beneficial to work together and have the potential to agree on actions/strategies/methods for solving their problems. The platform is usually organised on a European level and may be organised at the international level via mirror platform. The interconnection achieved with international partners brings particular relevance and dynamics into the exchange and multiplying activities.



**Figure 6.** Organic agricultural land share in Europe. (Source: <http://www.organic-world.net/yearbook/yearbook-2017/infographics.html>).

An important priority is to understand agricultural residues chain potentialities in a quantitative way through open dialogue between stakeholders, relevant and robust data/knowledge base and using decision support tools. Involving stakeholders from Europe and beyond into the dialogue represents a challenge as in many cases they are required to invest a significant amount of knowledge, time and effort without getting paid for that. Therefore, certain benefits should be provided for them; what they find valuable in return for their efforts invested and knowledge shared. The motives of the different stakeholders can vary; therefore, for successful collaboration as a first step it is suggested to use value chain analysis to identify the necessary members and their interest/motivation.



There are two particularly challenging steps in utilising the Stakeholder Platform. First the appropriate participants representing the key stakeholders of the selected value chains for valorisation of agro-waste have to be attracted to the platform through appealing offers for them, such as accessing information, knowledge, participation in an interactive learning form or networking opportunities. What benefits can be offered through harmonised efforts and collaboration of different local/regional value chains should be considered. The second challenging step is to maintain the interest and commitment of the stakeholders. In addition to web based information, consultations must be carried out, such as offering experimental methods, joint development of guidance materials on typical problems of a waste value chain, on applicable solutions, technologies, good practices, typical failures/traps to be avoided by using collaborative work space/file editor such as Google docs, web-based trainings etc. without forgetting face to face meetings and forum for future cooperation. Inventory and analysis of generation, characteristics, uses and conversion of agricultural residues following a value chain approach and focusing on selected geographic areas and agricultural product chains are intensified by opening the dialogue between industry, policy-makers, CSO and research representatives.

Particular attention has to be brought to organic agriculture, as defined by EC regulation 834/2007, 889/2008 etc. (European Commission, 2007b, 2008). Organic agriculture is holding approx. 7% of the EU agriculture surfaces, with higher percentages in some productions like wine or vegetables in specific regions (Figure 6). Organic agriculture products yield positive appreciation from consumers and citizens. Consequently, new valorisation roads in this domain can bring about products with high added value and new market opportunities. On the other hand, organic agriculture depends on closed (or almost-closed) circuits of nutriments, and the feedback has to be respected very carefully whenever nutriments or organic matter in important quantities are taken away from the agronomic level. The organic food processing and distribution sector is demanding strongly for sustainable inputs and can be a potent client for bioplastics (packaging material conforming to food packaging standards), biofuels etc. Consumers will accord higher acceptance and willingness to pay for products issued from organic agriculture residues.

To achieve better waste management strategies in terms of technical, environmental and socio-economic aspects, it is recommended to decipher the main technical, legal, environmental, business and behavioural barriers prior to implementing new business and marketing opportunities. Information tools, such as agricultural residue interactive databases and GIS, inventories of successful cases and good practice guidelines can provide input for environmental assessment and decision support tools.



Existing initiatives such as European Innovation Partnership (EIP) operational groups (e.g. EIP-Agri) as well as JU-BBI (Public Private Partnership in Bio-Based Industries), EIBI (European Industrial Bioenergy Initiative) and EBTP (European Biofuels Technology Platform) are expected to be expanded and supported by supplementing multi-stakeholders' engagements for collective actions for a sustainable agricultural residue management. Available information should be structured and converted into easily understandable user-friendly tools, such as short practical summaries of the methods, procedures and decision support tools, which can be disseminated to potential end-users through the existing initiatives and intermediators.

This approach has to be supported by improvements of legislative aspects. A strategic approach towards supporting the development of a lead market for agricultural residue based products should be supported by coherent, comprehensive and coordinated legislative and incentives actions, further streamlining and better targeting the existing ones, in particular in the areas of agriculture, the environment, health, transport, energy and industrial policy. In fact, there is no legislation that is setting specific targets for member states in relation to energy, chemicals and other materials production from organic and agricultural residue. Partly because information pertaining to the socio-economic and environmental benefits of biogas and bio-products is lacking. Apart from industry's self-commitment on bio-degradable polymer (voluntary certification and labelling scheme) and funds made available from member states to support biogas installations (Rural Development Regulation (EU) N° 1305/2013 (European Union, 2013)). Progress towards accurate regulatory and standard development with respect to environmental protection should be given serious consideration in the future based on a holistic and systematic evaluation of sustainability, incorporating regional as well as global impacts. The achieved impacts of regulatory developments are closely related to their adjustment to stakeholders' abilities and to realistic scenarios in the real environment. For example, the regulation of biogas in Germany and the subsidies and price guaranties has created a new market for these sub-products. Moreover, ensuring legal compliance should have acceptable enforcing costs by the targeted actors. Multi-stakeholders' platforms activities enable to better target, adjust and intensify the standardisation process by representing and connecting all the required stakeholders, including legislation representatives.

## Conclusions

The present paper intends to provide a transdisciplinary and holistic vision on how to coherently tackle some key research challenges related to

agricultural residues management, with regards to existing and missing scientific knowledge and to approach the related technological, social, economic and environmental impacts. The main conclusions and proposals for each identified challenge are pointed out below.

1. An adequate assessment approach which provides proper insight and guidance on the seasonality, regional aspects and complexity of agricultural residue management chains is still pending. Therefore, it is crucial to develop cross-disciplinary, multi-criteria, multi-scale and multi-actor environmental and economic performance assessment strategies (i.e. truly multi criteria decision tool) applicable to bioconversion technologies. It is important that these strategies are applicable already at the early stage of research and development (i.e. supporting eco-design already at bench scale). Indirect impacts of e.g. future technological developments within the society as a whole also needs to be considered and accounted for in order to judge true potentials of large investments in bioconversion technologies.
2. Conventional AD performance has to be improved based on geographical and seasonal AD waste feed streams and digestate nutrients distribution, and as well as by investigating new technological options to extend AD applicability (especially toward improving digestibility of lignocellulosic feedstock) and increase its eco-efficiency and end-products' (energy, nutrients and bio-polymers) safety and economic value.
3. Agricultural residues are a potential resource for the production of high-value chemicals provided that their complex and heterogeneous molecular structures are tackled by appropriate conversion into competitive products. Therefore, innovative eco-efficient and cost-effective cascading (upstream or downstream AD) conversion processes should be developed. Moreover, by enlarging both the spectrum of agricultural residue conversion technologies and the high-value, high-quality end-products port-folio, it should be possible to step up to a sustainable agricultural residue bio-refinery concept.
4. A cross-sectorial vision is needed to bridge the gap between agricultural residues science and business opportunities in order to promote an agricultural residue industrial ecology concept within a circular economy. It is essential to set up a real synergy on a local basis between the different agricultural and agro-industrial chains, the traditional food production activities, and the other industries for the effective use of agricultural resources, including residual resources, with sharing of environmental benefit and added value. Industrial ecology is required to generate eco-innovative multi-stakeholder opportunities and business models based on a certain scale size and where risks and added value are relevantly shared.

5. Since environmental- and socio-economic effects are multidimensional, a holistic approach should be developed in order to enhance materials and knowledge flow management. This could be achieved by promoting cross-sectors connection, exchange at appropriate local scales and capitalising on knowledge and information, in addition to fertilising life cycle thinking with territorial material flow analysis, in order to develop sustainable residual resources valorisation strategies. In brief, territorial “cyclifiers” connecting stakeholders and material streams should be developed.

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