Industrial Process Description for the Recovery of Agricultural Water From Digestate

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Currently, the reclamation and reuse of water have not reached their full potential, although more energy is needed to obtain and transport freshwater and this solution has a more serious environmental impact. Agricultural irrigation is, by far, the largest application of reclaimed water worldwide, so the proposed concept may result in the production of water that can be used, among others, for crop irrigation. This paper describes a novel installation for the recovery of the agricultural water from the digestate, along with the results of initial experiments. Currently, water is wasted, due to evaporation, in anaerobic digestion plants, as the effluent from dewatering of the digestate is discharged into lagoons. Moreover, water that stays within the interstitial space of the digestate is lost in a similar fashion. With increasing scarcity of water in rural areas, such waste should not be neglected. The study indicates that hydrothermal carbonization (HTC) enhances mechanical dewatering of the agricultural digestate and approximately 900 L of water can be recovered from one ton. Dewatered hydrochars had a lower heating value of almost 10 MJ/kg, indicating the possibility of using it as a fuel for the process. The aim of this Design Innovation Paper is to outline the newly developed concept of an installation that could enable recovery of water from, so far, the neglected resource—i.e., digestate from anaerobic digestion plants.

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Introduction

Given the growing demand from human activities and climate change issues, many regions, primarily in the south, face difficulties in providing enough freshwater to satisfy demand. It is estimated that in 2025, approximately 2/3 of the population (about 5.5 billion people) will live in areas exposed to so-called water stress. This means that the amount of renewable water resources (the so-called Falkenmark index) per person per year will be below 1700 m^3. About 1.8 billion people will live in areas with a significant water shortage (Falkenmark's value < 1000 m^3 per person per year). Currently, the reclamation and reuse of water have not reached their full potential, although more energy is needed to obtain and transport freshwater and this solution has a more serious environmental impact. In addition, the year-round water shortage affects 1/3 of the EU's territory, and the lack of water is still a serious problem for many EU member states. Increasingly unpredictable weather conditions, including severe droughts, may also affect the amount and quality of freshwater resources. Moreover, as water issues are inevitably linked with the food resources, this scarcity could detrimentally affect food production [1,2]. Agricultural irrigation is, by far, the largest application of reclaimed water worldwide, so proposed experiments may result in the production of water that can be used, among others, for crop irrigation. Moreover, the new water source will lead to savings for the economy and the environment and will contribute to better management of the most valuable resource, which is water. This year drought in Poland caused estimated losses of approximately 120 million EUR, with a significant impact on the livelihood of the inhabitants of 112,000 of small scale farms over an estimated area of 2 million hectares.[2] These farms are often the only source of income for whole families. In parts of the Netherlands, like Limburg and West Brabant, watering of the crops was banned because of too-low water levels.[3] Forest fires in Sweden claimed lives of at least one firefighter.[4] Moreover, over 80 wildfires, some of them within the arctic circle caused losses estimated to 60 million EUR.[5] Aid pledged to the farmers in Sweden, hit by extreme drought, amounts to approximately 320 million EUR.[6] The aim of this Design Innovation Paper is to outline the newly developed concept of an installation that could enable recovery of water from, so far, neglected resource—i.e., digestate from anaerobic digestion (AD) plants.

The Use of Hydrochar From Digestate—Possible Syneries Between Water Recovery, Use of Hydrochar as a Product, and Enchancement of the Anaerobic Digestion Process

The state-of-the-art biogas plant has a substantial land requirement for the storage of digestate, typically 8 ha/MW of installed power, which introduces significant costs [3]. Since digestate is rich in nutrients, land spreading is used as a utilization option. However, European Nitrates Directive (91/676/EEC) is a significant obstacle for wider implementation of this practice [4]. Currently, there are several commonly applied techniques for digestate management with solid–liquid separation being one of the possibilities. Thermal drying is considered as one of the options that, along with a subsequent pelletizing, might lead to a significant decrease in the volume of the digestate [5,6]. Nonetheless, it comes at a cost of the use of valuable energy, e.g., using a part of the produced biogas [5], with open-air drying being the only energy-saving option. The recovery of water after drying is typically neglected. There is a potential for the recovery of the nutrients in the digestate, with some synergy potentially existing between this stage and aforementioned purification of water. This is due to the fact that the ammonia stripping and struvite precipitation are necessary [5,7]. From the lifecycle point of view, these processes can become a good alternative to the Haber–Bosh process which can be characterized by high energy consumption, i.e., 37 GJ per ton of ammonia [8]. The research on the hydrothermal carbonization (HTC) so far has been focused mainly on its use as a thermal treatment for upgrading low-quality solid fuels [9]. HTC of the digestate has significant potential, as it could improve its subsequent dewatering [10], partially remove organic and inorganic materials, decrease the overall solid mass, sanitize the digestate, change its properties, and eliminate problems related with emissions of odors from the installation. Some amount of studies has already presented the successful use of the HTC liquid as a feedstock for anaerobic digestion [11,12]. However, a significant gap still exists in terms of a comprehensive analysis of the simultaneous influence of the process on both dewatering and feasibility of the liquid for anaerobic digestion. Further processing of the liquid fraction in order to its purification prior to discharge into the environment is often implemented with membrane separation [13]. It is often considered in this case as the only feasible method to purify water to such degree. Additionally, it allows recirculation for the recovery of the nutrients.

Biomass turned to biochar, in general, can improve the quality of the soil [14], which is true also for hydrochar [15]. However,

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[2] https://www.euractiv.pl/section/rolnictwowpr/news/susza-w-polsce-straty-przekroczyly-juz-pol-miliarda-zlotych/

[3] https://nltimes.nl/2018/06/25/record-drought-parts-netherlands

[4] https://www.ctif.org/news/fireman-died-swedish-wildfire-after-scorching-hot-month-may

[5] https://nordic.businessinsider.com/sweden-is-battling-historic-fires—asking-europe-for-help–

[6] https://apnews.com/d093b86631dd4ee28ee394ff7c7bb3bd/Sweden-sends-home-foreign-firefighters-as-wildfires-die-down

biochar offers some benefits in terms of serving as an additive for the anaerobic digestion by creating a habitable surface area for microbial cells [16], being a conductor of electron transfer among the species, a sorbent for inhibitors, and a reactant in the labile carbon methanization [17]. Positive effects of the addition of hydrochar to the anaerobic digestion have already been mentioned by the literature [18,19] for digestate coming from the AD of food waste or dead pig carcasses.

Various techniques are available for the purification of water [20–26]. For recovered water, typically, after preliminary cleaning (removal of ammonia and precipitation of struvite), ultrafiltration and reverse osmosis processes are used for purification of water [26]. Thus, traditional technology is focused mainly on the production of drinking water. Change of the focal point might allow saving precious resources of potable water by tapping to a typically neglected source of agricultural water. To fulfill this goal, an interdisciplinary approach, connecting many different technologies, is needed to create the necessary synergy. Nanofiltration is one of the most up-to-date techniques, which uses nanotechnology in the membrane water purification process. Currently, it is one of the most intensively developed membrane technologies. Like in reverse osmosis, using nanofiltration process, it is possible to get very high-quality water, however, not completely demineralized. A nanofiltration membrane removes multivalent ions, many micropollutants, inorganic compounds as well as pesticides, heavy metals, and nitrates. The nanofiltration membrane is capable of retaining organic compounds with a molecular weight greater than 200–300 Da and multivalent salts [5]. The water obtained in this way is microbiologically safe and suitable for use immediately after the completed process. Unlike reverse osmosis, nanofiltration requires lower operating pressures. An additional advantage is a fact that nanofiltration membranes have a longer lifespan compared to reverse osmosis membranes, which translates into lower operational expenditure (OPEX). Furthermore, taking into account the possibility of the presence of the volatile organic compounds in the permeate after nanofiltration, it is proposed to use an adsorption process as the final step of water purification. The constant search for new adsorption materials led to the usage of the magnetic biochars [6] and carbon nanotubes [27] for water and wastewater treatment. Huge interest in this material is related to their unique properties which have fundamental importance for their potential technological applications. Due to these special properties, it can be assumed that the efficiency of the process will be much higher than that for other sorbents, thereby allowing to obtain high-quality water. Unfortunately, there is still no information on the use of carbon nanotubes in the process of recovery of water from biogas plant wastewater. New processes are still being sought, which, with lower energy consumption, would effectively remove impurities from water solutions and thus would enable the recovery of water from waste streams. Undoubtedly, one of such processes may be the process of forward osmosis proposed in the research. Currently, this process is increasingly used in many fields of water and wastewater treatments. However, a small number of literature reports on the recovery of water from wastewater testifies to the rare usage of this process. Due to the numerous advantages of forward osmosis, it seems advisable to conduct research in this area. Thanks to this process, the recovered water could be used for crop irrigation, preparation of the fertilizer solution [8], or for the livestock. All proposed activities in the project will contribute to the development of highly effective technologies that will reduce water scarcity through the usage in agriculture water recovered from the AD of organic wastes.

There is a substantial customer base for systems that would enable poly-generation of multiple products, using digestate as the feedstock, as there is currently more than 17,600 biogas and 500 biomethane plants operating in Europe [28], producing more than 18 billion m^3 of biogas and more than 1200 million m^3 of biomethane [29]. In this environment, agricultural water, due to recent droughts, becomes an increasingly scarce resource. The proposed technology might open additional commercial opportunities in the rural areas around the world, where water is scarce, soil quality is poor, and agricultural residues are available (Africa, Caribbean, and South Pacific region). Worldwide biogas market size is estimated to exceed 32 billion USD by 2023,[7] whereas the waste-derived biogas market is estimated to be worth 10.1 billion USD by 2022.[8] Moreover, there is a huge worldwide potential for biochar due to problems with the quality of the soils and the content of organic matter [30]. Global soil treatment market is expected to exceed 39.5 billion USD by 2021.[9]

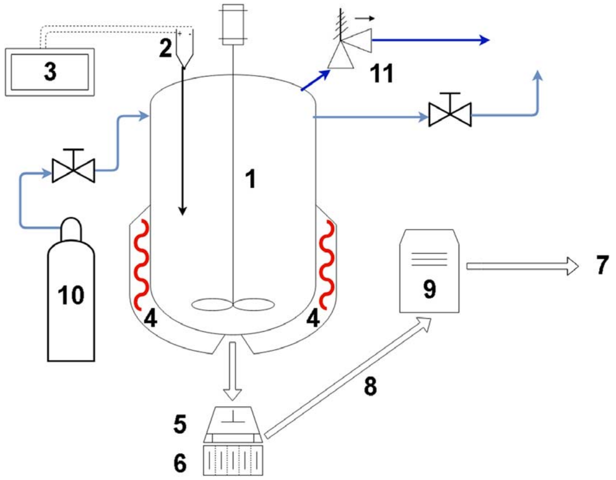

Fig. 1 Diagram of the test rig used for hydrothermal carbonization of the digestate (1—Autoclave; 2—type K thermocouple; 3—PLC controller; 4—heating mantle, with band heaters; 5—hydraulic press; 6—filter; 7—proximate analysis of the fuel; 8—hydrochar, after mechanical dewatering; 9—dryer; 10—nitrogen for purging; and 11—pressure relief valve)

Experimental Methods and Initial Results

The sample of the digestate was taken from an agricultural anaerobic digestion plant, at the outlet of the tank. The sampling procedure resembled the one specified in EN 14778:2011 "Solid biofuels—sampling" [31] for the specific case of sampling from stationary stockpiles. Each sample was taken from different parts of the pile in order to achieve a representative sample. In the case of the digestate of the wet fraction of municipal solid waste, the sample was additionally presorted and any visible, bulk size pieces, such as fragments of broken glass, whole objects made out of plastic etc., had been manually removed from the sample lot prior to the hydrothermal carbonization tests, as the presence of these objects cannot be avoided, even though the material is sorted, prior to the anaerobic digestion.

The diagram of the experimental setup (Fig. 1) shows both the autoclave rig as well as the hydraulic press that was used for the subsequent dewatering of the sewage sludge. HTC was performed in the autoclave filled with distilled water and digestate, in order to achieve the water to the dry biomass ratio of 12:1, calculated as a mass/mass ratio of the total water (distilled water and moisture in the biomass) to the mass of the dry-processed feedstock. The size of the processed sample was approximately 200 g of the dry mass of the feedstock.

After adding both biomass and water, the freeboard of the autoclave was purged by the nitrogen of technical purity. The autoclave vessel was heated up by a heating mantle, with band heaters. The temperature was measured by a K type thermocouple, connected

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[7] https://www.gminsights.com/industry-analysis/organic-biogas-market

[8] https://globenewswire.com/news-release/2018/05/01/1493708/0/en/Waste-derived-Biogas-Market-to-See-10-6-Annual-Growth-Through-2022.html

[9] https://www.marketresearchstore.com/news/global-soil-treatment-market-222

to a programmable logic controller (PLC). A setpoint temperature of 200 °C was chosen, as it is the fairly typical temperature for the HTC process, with most of the literature results presented for the range of temperatures between 200 °C and 260 °C [9,32,33]. Hydrothermal carbonization was performed under the water vapor saturation pressure at the specified process temperature. Residence time in the reactor was 270 min. Time measurement started after the autoclave reached the setpoint temperature. After 4.5 h, heating mantle was turned off, and the setup was left to cool down.

Mass yield (Y_m) and energy yield (Y_e) were used as typical performance indicators for the torrefaction process [34–37]. The mass yield was assessed, using the volatile matter content of both feedstock and product, as proposed by Weber et al. [35]:

$$Y_m = \frac{1 - VM_{feedstock}}{VM_{product}} \tag{1}$$

The energy yield was calculated using the well-established formula [36,38,39]:

$$Y_e = Y_m \cdot \frac{HHV_{feedstock}}{HHV_{product}} \tag{2}$$

In order to assess how much of the inorganic substance remained in the solid product, the ash yield (Y_a) value was used, as suggested by Wnukowski et al. [32] and Moscicki et al. [9]:

$$Y_a = Y_m \cdot \frac{A_{product}}{A_{feedstock}} \tag{3}$$

Additionally, the need for assessing the potential of the water recovery created the need for additional coefficient. The water yield (Y_w) was developed, defined as the normalized amount of water left in the hydrothermally carbonized product after mechanical dewatering. It can be calculated according to the formula:

$$Y_w = Y_m \cdot \frac{MC_{product}}{MC_{feedstock}} \tag{4}$$

Description of the Proposed Industrial Process

This Design Innovation Paper presents a modular and transportable installation for the staged recovery of the agricultural water, from dewatering and drying of high moisture fermentation products. Each of the modules will fit into standard containers along with all the auxiliary devices, thus making the whole installation work according to the Plug and Produce (PnP) principle. The most important part of this installation is the water reclamation module. The use of the ultrafiltration process will allow the retention of residues of organics, nutrients, colloids, and microorganisms. The nanofiltration process will separate multivalent ions and high molecular weight organic compounds. Low molecular weight organic compounds will be separated, using produced hydrochar, as well as other carbon-based materials, e.g., carbon nanotubes, in an adsorption process. A combination of polymer and ceramic membranes with various molecular weight cutoff shall be implemented, with appropriate separation and transport properties. Moreover, the installation is supposed to reap the benefits of the HTC process. Optimization is necessary in a context of factors such as suitability of the liquid for subsequent digestion, dewaterability of the obtained hydrochars, suitability of the produced hydrochars for the use as soil amendments, suitability of the produced hydrochars for the use as a adsorbent for water purification, and suitability for the use of hydrochars as a solid fuel. Also, recovery of water through subsequent drying and condensing possible due to using of low-quality heat is an important feature of the proposed solution. Reaching the maximum productivity of the installation that would still allow maintaining its modular and transportable nature is also an important factor. Turning byproducts into useful/marketable products (e.g., magnetic biochar) and the optimum size of the accumulation tank that would allow maximizing the use of cheap, off-peak electricity are also features of vital importance when economic feasibility is considered.

One of the activities ensuring further food production without exposing the natural environment to a water shortage at the same time should be the increase of water usage efficiency. Agriculture affects both the quantity and the quality of water available for other purposes. Irrigation of crops is one of the areas of agriculture in which significant improvement can be achieved through the introduction of new practices and strategies for the water recovery from treated wastewater. Therefore, a direct competition for available water reservoirs should be avoided, especially if alternative sources of agricultural water are available. Sustainable Development Goals proposed by UN, as well as the international agreement signed in Paris during COP21, are currently important drivers of the international research and development efforts in order to achieve the highest possible sustainability of the human activities. The project described in this proposal addresses these needs by research and development, aimed at obtaining a technical design of an installation for the staged recovery of agricultural water from high moisture fermentation products. The general flowsheet of the concept is depicted in Fig. 2.

In order to recover water from the liquid fraction after digestate dehydration, it is proposed to apply the integrated membrane process composed of the pretreatment stage and the membrane process of actual purification after the initial phase (Fig. 2). Due to the fact that it is likely that the permeate after the nanofiltration process may contain low molecular weight fractions of volatile organic compounds, it is proposed to apply the adsorption process as a post-treatment stage. These methods are highly appreciated due to their efficiency, simplicity, and relatively low process costs. The proposed adsorbent materials for further permeate purification are, among others, hydrochars, magnetized hydrochars, and multi-walled carbon nanotubes. They are characterized by unique properties, among others: large surface area, high mechanical durability, and adsorption capacity [40,41]. The proposed technology of complete purification (Fig. 2) will allow to purify the digestate liquid fraction and obtain water that may be applied, among others, in agricultural production. Both polymer and ceramic membranes with various molecular weight cutoff can be used for this purpose. Separation and transport properties of the tested membranes will be determined. Among other factors, the effect of membrane type, its molecular weight cutoff, trans-membrane pressure and membrane operation time on the quality and the permeate volume flux, as well as membrane susceptibility to fouling, will be investigated. As an alternative to water recovery using pressure-driven membrane processes, a forward osmosis process [42], using non-porous asymmetric membranes made of hydrophilic polymers, could be applied. In this process, conducted under atmospheric pressure, the water will pass through the synthetic membrane from the liquid phase of the digestate to the concentrated receiving solution. The driving force of the process will be produced in a natural way and will result from the difference in the osmotic pressure of solutions on the two sides of the membrane. The process may take place until the hydraulic and osmotic pressures is equal. In this case, a fertilizer concentrate will be used as the receiving solution. The water from the digestate moving through the membrane will, therefore, be used to dilute this concentrate with initial concentration being too high for the direct application to the plant fertilization.

It will focus on the reclamation of water from the liquid fraction obtained after digestate dewatering and post-condensation water from the drying process of the solid digestate fraction, which will be turned into a marketable product. The recovered water from both sources can be reused for agricultural irrigation. As a result, farmers will have access to a sustainable water supply for cultivation. The proposed technology guarantees that any additional hazards will be eliminated and the recovered water will be safe. As a result, consumers will be sure that the products they consume are safe and companies will have more development opportunities. An additional benefit of the proposed technology of water recovery from digestate

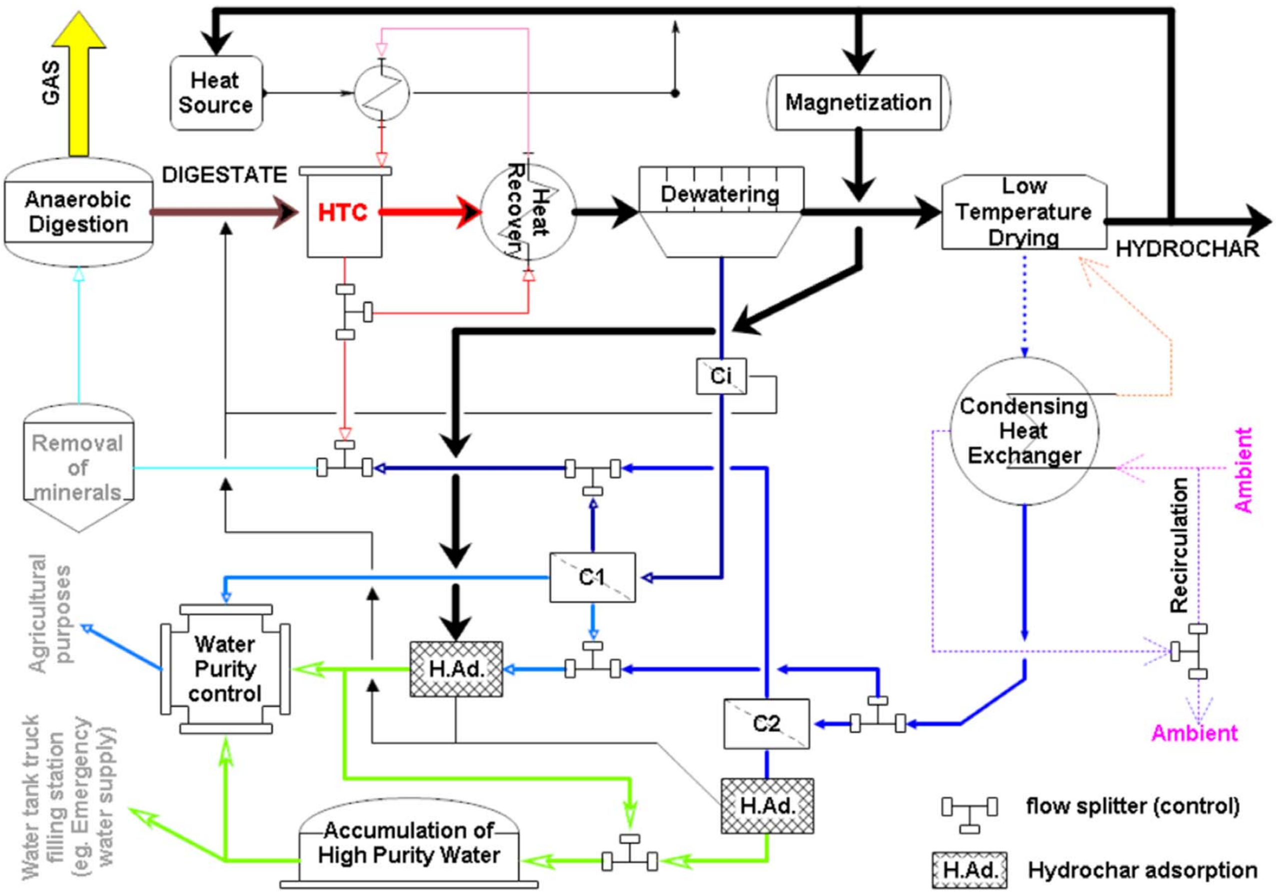

Fig. 2 Process flow diagram of the proposed technology for the recovery of agricultural water from digestates (HTC—hydrothermal carbonization; Ci—ultrafiltration; C1 and C2—nanofiltration, using different types of membranes)

may be the reuse of the resulting concentrate after membrane processes: it may be recycled to the fermentation chamber, and thus correct the water content of the fermented mass. Thanks to the use of concentrate, the proposed process may be a waste-free technology (zero liquid discharge technology), in compliance with the rules of the circular economy.

Results of the initial investigation are very promising, as the obtained water yield (Fig. 3) indicates that a significant amount of water can be recovered. It can be calculated quite easily that per single ton of wet digestate, from the digester tank, approximately 900 L of water can be recovered. However, further purification of this liquid would probably needed, which should be a subject of future investigations. Nonetheless, this enhancement, along with the fact that the initially negative lower heating value (Table 1) can be improved to almost 10 MJ/kg, just with simple mechanical dewatering, shows a significant potential of the proposed technology.

In order to obtain sensible energy balance of the process, the improvement brought by the mechanical dewatering should outweigh the loss of physical enthalpy due to the heating of water. Recovery can and should be introduced; however, some inefficiency in the recovery of physical enthalpy of the HTC liquid should always be expected. Nonetheless, even with relatively low efficiency of such recovery, the gain obtained by enhanced dewatering can improve the overall heat balance, as depicted in Fig. 4.

The proposed technology will be modular and transportable, thanks to the containerization of all of the modules. This innovative, transdisciplinary approach could enable access to the potential water resources, currently neglected, i.e., water present in solid fermentation products with high moisture content. Moreover, the project is aiming to achieve high synergy by integrating the water recovery with improved heat balance of the drying process and additional utilization of the latent heat that could be recovered during the water condensation. Furthermore, the use of HTC, thus, bringing the potential for synergy due to positive effects in terms of dewaterability, sanitization, and recovery of organics for

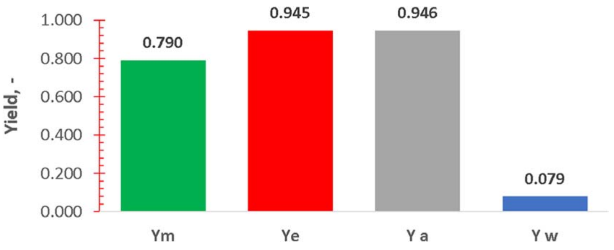

Fig. 3 Yields of the HTC process performed using the digestate from the agricultural biogas plant

Table 1 Proximate analysis of the raw and hydrothermally carbonized digestate (ash—ash content, %; db—dry basis; wb—wet basis)

Sample	Ash (%^{db})	VM, (%^{db})	MC, (%^{wb})	HHV, (MJ/kg)	LHV, (MJ/kg)
Digestate after anaerobic digestion	8.1	63.6	91.3	19.74	−0.64
Digestate after HTC and mechanical dewatering	9.7	53.9	51.3	23.63	9.63

Note: LHV, lower heating value.

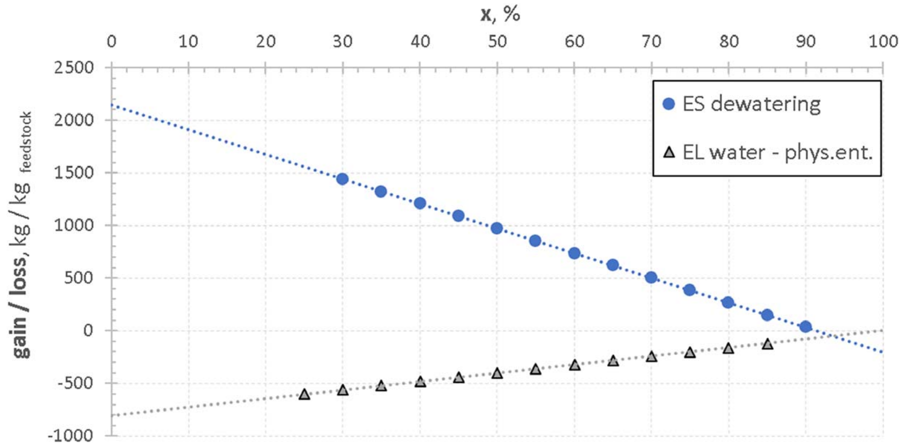

Fig. 4 Energy loss due to the inefficiency in the recovery of physical enthalpy of the HTC liquid and energy savings attributed to mechanical dewatering; *x* indicates moisture content after dewatering for ES and efficiency of heat recovery for EL.

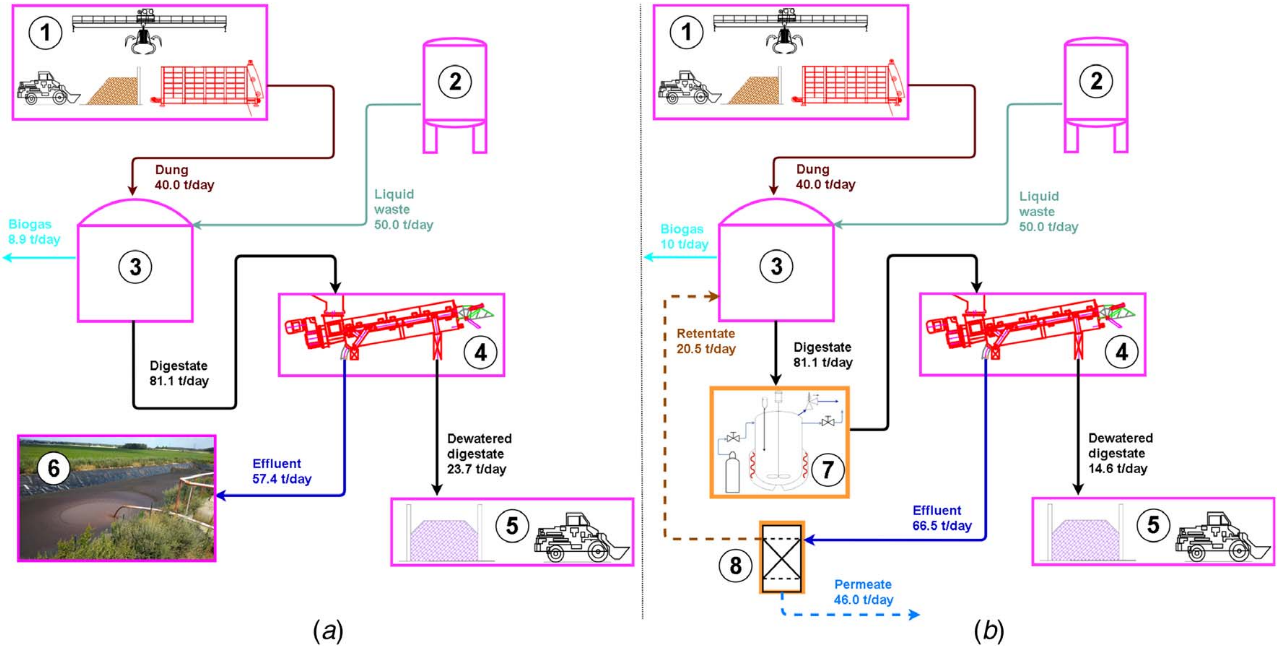

Fig. 5 Mass balance of an agricultural anaerobic digestion plant (*a*) and assumed balance after the addition of new unit operations (*b*—orange frames, units 7 and 8) (1—solid feedstock loading; 2—liquid feedstock loading; 3—digester; 4—mechanical dewatering; 5—digestate bunker; 6—lagoon; 7—HTC reactor; 8—membrane purification installation)

the anaerobic digestion. Purification of the water from two separately obtained streams will be achieved by the use of different types of membrane processes as well as sophisticated carbon-based materials, such as magnetic chars and nanotubes, selected in a way, that will optimize the use of the electricity by the installation as well as capital expenditure (CAPEX) and maintenance cost. The use of electricity will be further optimized by the implementation of accumulation of pure water, allowing to minimize the cost of electricity by using it during off-peak hours. This will make the proposed technology "smart grid ready." It will also allow better management and ensure the availability of this precious resource in case of emergency situations, for example, water for firefighting squads during wildfires. An additional benefit of the proposed technology of water recovery from digestate will be the reuse of the resulting concentrate: it will be recycled to the waste processing as a technological liquid to the fermentation chamber, which will increase the hydration in the digestion chamber. Due to the use of concentrate, it will be a waste-free technology (zero liquid discharge technology). Finally, the proposed installation will allow to turn digestate into a valuable and marketable product.

The proposed way of integration of some of the modules of this new concept, within existing anaerobic digestion, is shown in Fig. 5 along with the mass balances for both cases. The configuration and mass balance of the "state-of-the-art" anaerobic digestion plant (Fig. 5(*a*)) were made based on a case study of a plant located near a cattle farm and a distillery (Silesia region, Poland). For the case of the modernized plant, with HTC and membrane separation included (Fig. 5(*b*)), it was assumed, based on initial results, that the retentate to permeate ratio is 30:70 and that all of the organic matter, recirculated back to the digester, is converted to biogas and additionally does not influence the digestion of original feedstocks in a detrimental way.

The proposed solution could be summarized as follows:

- Modular nature of the design allowing swift integration with the existing infrastructure in more than one stage, i.e., not all of the modules have to be introduces at the same time (compare Figs. 3 and 5(*b*)).

- Utilization of membranes requiring lower pressure (in comparison with state-of-the-art solutions) and utilization of a part of the hydrochar stream and magnetic hydrochar for filter columns.
- Sustainability of the technology by utilization of a low-grade heat (the latent heat of vaporization) for drying and a part of the hydrochar stream as a fuel for the heat source for the hydrothermal carbonization.
- The unique solution to make the hydrochar as magnetic biochar for wastewater application.
- Zero waste and zero liquid discharge technologies, thanks to recirculation of the reject liquid (retentate) back to the anaerobic digestion.
- "Smart grid ready"—possibility for active management of the demand side and use of the electricity with marginal price by including the water accumulation unit.
- Enabling sustainable management of water resources by using streams that are presently neglected.

Increased availability of the water due to its recovery from the digestate will decrease the pressure on available resources of potable water in rural areas, where frequent droughts are a problem, thus improving the wellbeing of the local population. Accumulation of water, included in the design, could potentially help to save people's lives when used by firefighting squads during fires, which are more likely during natural disasters such as droughts. Improvements in the quality of the soil due to application of hydrochar as a soil amendment will have a positive influence on the agricultural sector by increased yield during crops. The containerized system will give additional commercial opportunities for the technology developer due to a possibility to sell units to more distant markets, with special emphasis on third world countries, where projects tend to be expensive during the erection of the installations due to low availability of highly skilled workforce. Thus, pre-assembled, containerized installations, with low investment cost, might become an opportunity for inhabitants of underdeveloped countries to save their precious, often scarce, water resources. The self-sustainable character of the installation and implementation of the accumulation will open new markets in remote, off-grid locations such as underdeveloped countries and islands (Caribbean's and South Pacific regions). Overall designed technology will be a step forward toward worldwide implementation of the circular economy. Further research is needed in order to determine a full mass and energy balance for all the modules of the installation.

Conclusions

Proposed implementation and wide use of such an installation can significantly contribute to the practical implementation of the UN Sustainable Development Goals, as well as to the implementation of the conclusions of the COP 21 Paris Agreement, in a cost-effective way, by developing a modular and transportable installation for the purification of the water from the digestate for agricultural use (livestock drinking water and irrigation). Significant contributions to the goals of the Horizon 2020 can be made. The unique approach toward the optimization of the energy use, by the proposed technology, is in line with the concept of the greening of the economy. This can be achieved by maximizing the synergy between increased energy efficiency, through the use of waste, low-quality heat, and optimization of the use of electricity via accumulation of the purified water. The latter will also help to include more intermittent energy sources (e.g., solar and wind) into the energy grid by stabilizing it on the demand side, according to the principles of a smart grid. Electricity necessary for the pumps needed for membrane purification modules will be consumed primarily during periods with high availability of the solar and wind energy and off-peak hours. Utilizing underappreciated water resource (water in the digestate) will contribute toward closing of the water gap. Moreover, the ability of the installation to produce hydrochar (a potential substitute for activated carbon) could help on the way toward new solutions for sustainable production of raw materials. Another potential use of hydrochar, as a soil amendment, could help in achieving sustainable food security, as envisioned in H2020. Recirculation of the water, containing hydrocarbons, back to the anaerobic digester, thus making the technology, zero waste (zero discharge) is in line with the goal of achieving circular economy. The study indicates that approximately 920 L of water can be recovered from one ton of the digestate, due to enhancement of the mechanical dewatering, by the process of hydrothermal carbonization. Dewatered hydrochars had a lower heating value of almost 10 MJ/kg, indicating the possibility of using it as a fuel for the process.

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Nomenclature

$A_{feedstock}$ = ash content of feedstock (dry basis), $\%_{\mathrm{dry}}$
$A_{product}$ = ash content of the product (dry basis), $\%_{\mathrm{dry}}$
Y_a = ash yield
Y_e = energy yield
Y_m = mass yield
Y_w = water yield
$HHV_{feedstock}$ = higher heating value of feedstock, MJ/kg
$HHV_{product}$ = higher heating value of the product, MJ/kg
HTC = hydrothermal carbonization
$MC_{feedstock}$ = moisture content of feedstock (dry basis), $\%_{\mathrm{dry}}$
$MC_{product}$ = moisture content of product (dry basis), $\%_{\mathrm{dry}}$
$VM_{feedstock}$ = volatile matter content of feedstock (dry basis), $\%_{\mathrm{dry}}$
$VM_{product}$ = volatile matter content of the product (dry basis), $\%_{\mathrm{dry}}$

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