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Sustainable Energy from agro-industrial wastewaters in Latin-America

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ABSTRACT

Conventional biological processes used to treat high-polluted agro-industrial effluents produce biogas and sludge, two by-products stocking up important energy contents. Advanced biotechnologies to treat these effluents are being developed to obtain increased biogas production and other efficient and useful energy sources, such as bio-hydrogen and even bio-electricity. Utilization of these clean energies is significantly lower than other renewables, particularly in developing regions such as Latin-America. This occurs despite the close link between the environmental benefits and sustainable use of this energy, which might be incorporated in different sustainable strategies for local and regional development. This study reviews the 'state of the art' of Latin-American research regarding technologies for energy recovery from agro-industrial wastewaters and their sustainable implementation. It also discusses the need for a more sustainable management of the water-energy nexus in treatment systems used to decont minate effluents, which should be committed to the improvement of renewable energy production and to a more extended regional use. Contributions of methodologies based on life cycle assessment (LCA) and criteria-indicators used to drive sustainability studies in this field are updated and used to outline a conceptual framework advising sustainable practices in this sector.

Contents

Abbreviations: BOD, Biochemical Oxygen Demand; COD, Chemical Oxygen Demand; TSS, Total Suspended Solids; TNK, Total Kjeldahl Nitrogen; WWTs, Wastewater treatment systems; ai-WWTs, Agro-industrial wastewater treatment systems; CDM, Clean Development Mechanisms; LCA, life cycle assessment; MFCs, Microbial fuel cells; CWWT, Combined Wastewater Treatment; UASB, Up-flow anaerobic sludge blanket; GHG, Greenhouse gases; MCA, Multi-criteria Analysis; LCSA, Life cycle sustainability assessment; SDIs, Sustainable Development Indicators; SPS, Substantial Principles of Sustainability

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1. Introduction: wastewaters as energy source

Worldwide, wastewater treatment systems (WWTs) are increasingly engaged into providing improved environmental remediation and simultaneously into increasing energy production. Public and private sanitation, as well as industrial sectors, are searching for ways of enhancing the energy production during the treatment of their liquid effluents [1–3]. Energy potential of wastewaters is represented by their contributions to thermal energy, recovery of selected pollutants (nutrients, chemicals, bioproducts, etc.) and chemical–biochemical energy present in the dissolved and suspended organic pollutants [3,4]. The latter one is the easiest accessible energy form in most of the effluents being treated by biological process, because organic pollution is removed by yielding methane-rich biogas and sludge as main by-products. Biogas and sludge capture most of the chemical energy originally contained in the polluted effluents, becoming useful energy carriers [3,5]. Nevertheless, utilization of biogas from WWTs is significantly lower than the use of landfill and agricultural biogases, even in developed contexts [6,7]. Meanwhile, in low-economy regions, composting of sludge is preferred, possibly because implementing thermochemical processes is more demanding in terms of knowledge and the initial investment required [8,9].

This paper examines the effluents from agro-industrial activities as their elevated concentrations of organic matter (>1000 mg COD/L) enable their conversion into energy. The focus is on Latin America because food production and first generation biofuels are industries that have shown sustained growth in the tropical and subtropical climates in the American continent [10,11]. The pressure on the environment as a result of the economic boom of these activities generates sensitive hot spots requiring immediate attention; for example, intensive use of agrochemicals, unforeseen socio-cultural transformations and increasingly polluted effluents [12]. Currently, there are not updated inventories of coverage and effectiveness of the wastewater treatment used by the Latin-American agro-industry and, in all probability, water-bodies are being affected beyond predicted levels. Furthermore, the wasting of potential energy from WWTs is closely interlinked with the poor quality of the provided treatment.

By contrast, the evaluation of the energy potential of diverse effluents is an ongoing task in various countries and introduction of wastewater treatment processes focused on enhanced energy production is a relevant topic for governments and industry [13,14]. A study in New Zealand shows that effluents from agricultural/agro-industrial activities comprise approximately 76% of the energy inventory in the wastewater sector [15]. This study also revealed that developing a smart technological evolution of WWTs makes it possible to increase the energy potential six fold. Another study has shown that Malaysia has improved the anaerobic wastewater processes used in the palm oil mills, the main agroindustry, by means of Clean Development Mechanisms (CDM), thus enhancing the availability of electricity derived from biogas. Moreover, Malaysia has begun a serious program of surveillance of modern wastewater technologies, involving biohydrogen production and water remediation by microalgae utilization [16,17].

This paper seeks to promote similar initiatives in Latin-America that will entail increased use of energy and a bigger participation of the energy produced from agro-industrial WWTs in projects committed to well-defined sustainability principles. Thus, this paper discusses this issue through different approaches, as follows. Firstly, it unveils the characteristics of the so called water-energy nexus in WWTs as a key principle of sustainability and it also analyzes some of the main bottlenecks that restrict a major use of wastewaters as energy sources in Latin-America. The second section sets out current and future bio-processes with potential to be used as WWTs and effective energy producers. The third section focuses on the contributions of the Life Cycle Assessment (LCA) methodology in the field of sustainability assessment for WWTs and emphasizes the crucial management of the water-energy nexus in agro-industrial wastewater treatment systems (ai-WWTs), suggesting a more representative evaluation of their declared energy function as sustainability criteria. Lastly, the paper discusses future prospects.

2. Assets of the water-energy nexus in WWTs

Currently, there are important initiatives recognizing the improvements required in the wastewater treatment infrastructure, that emphasize the inalienable synergies between water and energy in the field of environmental sanitation [18,19] and new technologies for environmental bioremediation promise to obtain enhanced biogas production, biohydrogen, direct bioelectricity and more effective energy pathways as described in the next section. Nevertheless, there is no clear evidence to show that these energy sources are being used, which would answer a certain number of economic, social and ecological concerns.

Firstly, WWTs can be at the same time consumers and potential energy producers. Secondly, energy from biogas or sludge offsets fossil energy and claims mitigation of CO_2 emissions. Nonetheless, WWTs are also liable to generate greenhouse gas emissions, methane (CH_4) present in released biogas and nitrous oxide (N_2O) produced by some wastewater treatments and nitrogen-rich effluents [20]. Moreover, small-scale production or high purification costs often make the exploitation of these energy sources prohibitive [6]. Finally, policies and tax benefits implemented to boost the use of first-generation biofuels have neglected energy projects in the wastewater and waste management activities. These barriers are more significant in developing countries due to lack of appropriate infrastructure and concerted action in the implementation of the environmental legislative framework, as well as limited involvement of small producers of renewable energy [21–23]. A quite different situation is observed in Europe, where the development of renewables has been clearly oriented by climate and energy diversification policies [24,25].

In Latin-America, biogas and sludge obtained from WWTs compete with waste biomasses, landfill biogas and fuels obtained from biological feedstocks [22]. Biogas also competes with natural gas, which is highly available at low prices in a number of countries in the region [26]. As a result, projects using energy from WWTs face various constraints. Biogas flaring and composting of sludge are default practices rather than their utilization as energy sources. In addition, the CDM has fostered the burning of biogas as the simplest way to grant carbon credits, without involving effectively this renewable energy in local development projects, such as, supplying low-cost energy to vulnerable communities [27].

Table 1
Physicochemical characterization of some agro-industrial effluents in the Latin-American Region and their energy potential.[a]

Activity (Country)	WWT Tipology		Flow (L/s)	*Physicochemical Parameters*						pH	Energy Potential	Prevailing practices that reduce energy utilization from aiWWTs
	Effluent	Usual Treatment Type		COD (g/L)	BOD_5/DQO	TSS (g/L)	O&G[b] (mg/L)	N_{TOTAL} (mg/L)	P_{TOTAL} (mg/L)			
Ethanol from sugar-cane (BRA)	Bulk Effluent (Vinasses)	Stabilization/ retention open ponds	2–6	20–65	0.5–0.6	__	~8	> 280	__	3.5–5.0	Biogas availability range between 2000 to 12000 m^3/d.	Ferti-irrigation with raw vinasses.
Tequila spirits production from Agave (MEX)	Bulk Effluent (Vinasses)	Stabilization/ retention open ponds	1.5–3	25–120	> 0.6	> 20	__	> 1100	> 40	3.2–4.1		
Palm oil mills (COL)	Bulk effluent after grease traps	Uncovered lagoon or Covered anaerobic ponds	2–18	35–90	0.4–0.66	5–60	–	100–1500	__	3.5–5.5	Capacity to produce 20000 to 26000 kWh/d treating anaerobically a flow of 6 L/s.	Projects for electricity cogeneration depend of local regulations to plug into the interconnected system.
Poultry Slaughter-house (MEX)	Bulk effluent after grease traps	DAF[b] or hydrocyclones	10–20	5–12	> 0.7	~2	150–700	70–100	> 9.0	6.0–7.4	Calorific power of physico-chemical sludge (DM)[b] range between 4000 to 5000 cal/g.	Replacement of anaerobic process by physicochemical treatments and handling of a bulk effluent treatment strategy.
Poultry-Vicera Processing (COL)	Bulk effluent after grease traps	UASB / EGSB	1–2	> 1.8	~0.7	> 0.3	> 250	> 55	< 0.01	5.0–8.0	Capacity to supply 2000 MJ/d of heat with biogas	
Dairy/cheese production (COL - MEX)	Bulk effluent free of whey after grase traps	DAF + UASB + Trickling filter DAF + UASB DAF + UASB + Activated Sludge	2–15	3.5–7.5	0.58–0.71	1–3	~800	> 60	~5	5.5–9.5	Capacity to drive an engine or micro-turbine (~ 100 kW)	Separation of whey reduces 80 to 90% the initial COD load. Furthermore, DAF pre-treatment removes 40 to 50% of the remaining COD, declining significantly the interest in biogas use.

[a] Reported data coming from the accumulated experience of the research groups involved in this work.
[b] O&G: Oil and Grease; DAF: Dissolved Air Flotation; DM: Dry Matter; BRA: Brazil; COL: Colombia; MEX: Mexico.

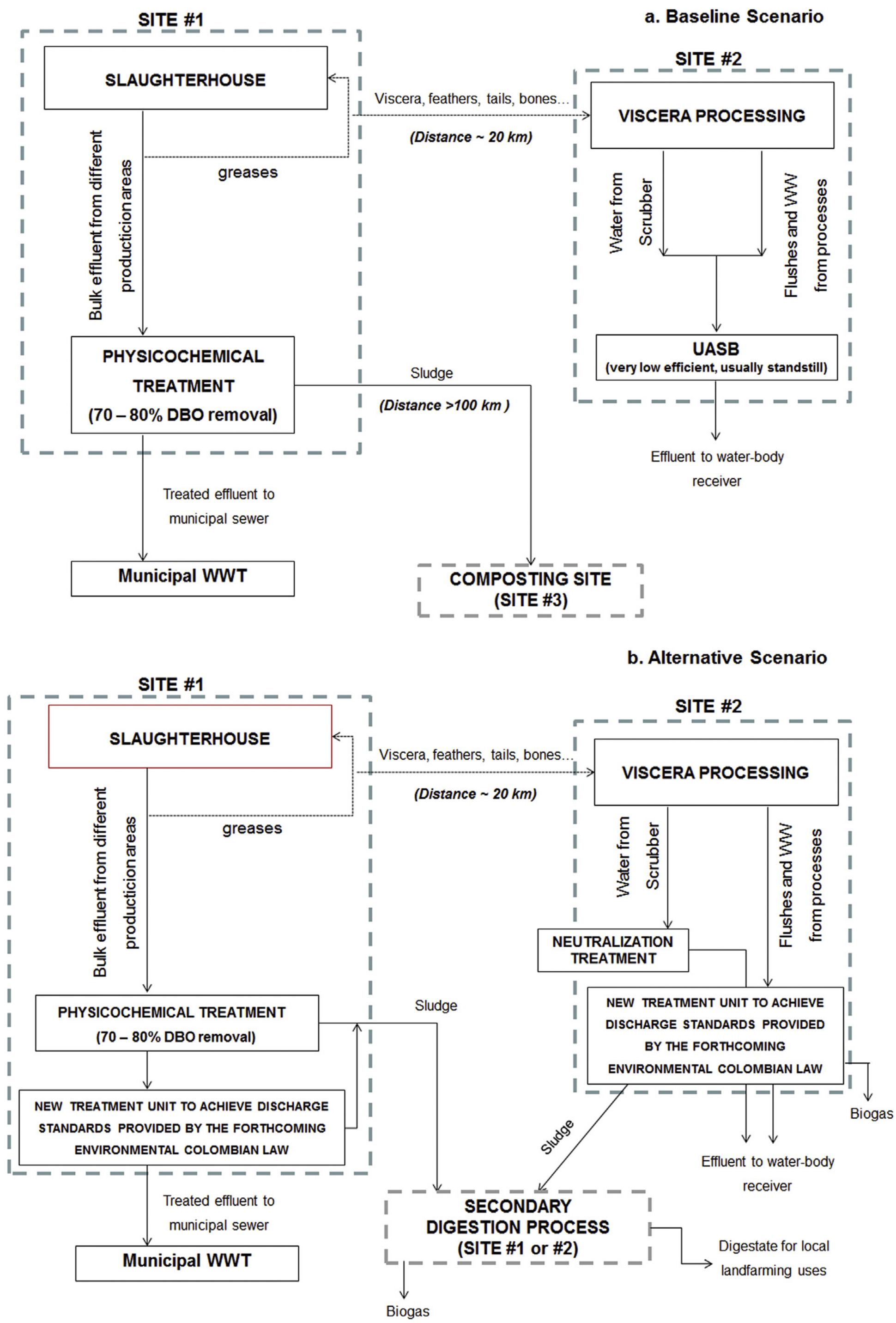

Fig. 1. Scenarios for integration of WWTs byproducts into one Colombian poultry agroindustry.

3. Energy recovery from agro-industrial effluents treatment

3.1. Current status in Latin-America

Effluents from agro-industrial processes have various options of biological treatment. When aerobic treatment is provided, high standards of water quality are achieved at the expense of elevated electricity requirements for aeration and sludge dewatering. On the other side, anaerobic processes offer lower operational costs and positive energy balance through production of methane-rich biogas [28]. High-rate anaerobic processes are competitive with aerobic ones in regard to organic matter removal, but it is necessary to recognize that exclusive application of anaerobic processes without post-treatment is only possible due to the lax standards for nutrients discharge in some contexts.

Particularly, ai-WWTs operating in emerging regions are frequently affected by underestimation of the treatment capacity, because a rigorous characterization of effluents is not often considered during the design stages. Moreover, some operational prevailing practices, such as mixing of effluents from different stages of the productive process, increase the chemical complexity of the combined effluent reducing the effectiveness of WWTs. Consequently, an important energy amount remains in effluents as not removed Biochemical Oxygen Demand (BOD), discouraging its exploitation as biogas or sludge as it becomes unaffordable. Without a complete understanding of how to use the energy potential of their effluents, some agro-industries prefer to install physicochemical processes as the main treatment [29,30], wasting the opportunity to include biological processes with more options for energy recovery [31,32]. As a result, agro-industrial effluents are poorly treated, triggering a series of adverse environmental impacts with low cost-effective utilization of their energy potential. Table 1 shows the physicochemical characteristics of some effluents produced by selected Brazilian, Colombian and Mexican agro-industries along with the potential energy flows resulting from their WWTs. Most of these selected agro-industries fail to make use of the bioenergy produced. An exception is the case of the palm oil mill "Tequendama", which exceeds 80% its own electricity demand by cogeneration with biogas from the anaerobic WWTs. This surplus will be supplied to an industrial park in the North of Colombia [33]. Similarly, in the province of "Tucuman", Argentina, projects with bioenergy from ai-WWTs are highly prized in the local energy market. This region has a 10000 m^3/d biogas potential to derive from effluents from lemon fruits processing plants and it plans to produce 90 MWe of heat and power from the anaerobic treatment of sugarcane vinasses [34].

It has also been demonstrated that agro-industrial effluents improve their energy potential through co-digestion with other organic wastes, as this process enables more stable and higher biogas production [35,36]. However, in practice, sustainable linkages between compatible wastes outside and inside the boundaries of the productive activity are not always easily available. For example, poultry processing is the main food industry in the North-East of Colombia, but of some concern is the relative isolation between different production units which hinders the integrated handling and treatment of effluents. Particularly, the sludge resulting from WWTs operation requires transportation for end-disposal, while the options for biogas utilization are bypassed due to capacity and efficiency constraints of existing WWTs. Fig. 1a illustrates the typical boundaries and linkages between some of the main processing facilities in this industry (Baseline scenario). The slaughterhouse, processing plant and the site for end-disposal of sludge produced in WWTs are shown as being "roughly short distance separated", but without opportunity for energy recovery. Opportunities for improving integration levels in this industry might consist of implementing alternative scenarios as presented in Fig. 1b. This scenario aims to enhance the on-site processing of sludge as well as improving the availability of biogas on nearby production sites.

3.2. Global and Latin-American research trends: advanced WWT technologies for energy recovery

Nowadays, new biotechnologies are being developed with the intention of increasing the energy potential of WWTs [3,37]. Table 2 summarizes some advantages, potential and issues that need addressing in those technologies considered the most

Table 2
Main bioprocesses under development for enhanced recovery of energy in WWT.

Bioprocesses	Advantages /Expectations	Potential for scale-up	Selected researches in Latin-America
Bio-hydrogen ($Bio\text{-}H_2$)	$Bio\text{-}H_2$ has higher energy density than bio-methane and is a cleaner and efficient feed-stock for fuel cells. It is a raw material adaptable to participate in different industrial processes [38,39].	Bio-photolysis, photo-fermentation and dark-fermentation are the bioprocess showing the highest potential, especially to treat effluents with high content of lipids and sugars [40,41]. Co-fermentation with easily degradable organic compounds (e.g. glycerol) increases the combined production of H_2 and CH_4 [36,40].	BRAZIL: The University of Sao Paulo and the Federal University of Sao Carlos, both settled in Sao Paulo City, have stressed a regional leadership in research about biological production of hydrogen by fermentative processes. Their researches involves analysis of $Bio\text{-}H_2$ potential of industrial wastewaters, particularly those containing vinasses and glycerol, main residues from the powerful Brazilian biofuels industry, and the study of different configurations of packed-bed reactors in this processes [48,49].
Micro-algae	Lower water footprint in the supply-chain of biofuels, recovery of nutrients (N, P) and CO2 capture [42,43]. Bio-oils extracted from different algal-biomasses are adaptable feedstock for biodiesel and biogas production [43,44].	Definitive development requires bioreactors offering ease operational and smaller production areas and significant improvement of technologies for desalination and dewatering of algal-biomass. Thermochemical valorization of algal biomass is also feasible. Pyrolysis of algal-biomass yields oils with similar calorific power to biodiesel [43,44].	COLOMBIA: Pr. V. Kafarov's research group at Industrial University of Santander-UIS (Bucaramanga) introduces LCA methodology to study biodiesel production from *Chlorella sp.*, cultivated in different substrates [50]. MEXICO: Pr (Ms). E. Olguín from the Institute of Ecology (Veracruz) does an analysis of a dual purpose micro-algae/bacteria system to treat different wastewaters (municipal, seawater and animal wastewaters as part of one integrated biorefinery producing biodiesel, biogas and chemicals [51].
MFCs	Flexibility to produce "bio-electricity" or bio-hydrogen when is set as MEC (Microbial Electrolytic Cell) [37,45].	The principles and challenges of this technology to achieve full-scale application are widely treated in a recent review [45]. MEC configuration might be closer than MFC to fulfill conditions for industrial application, being integrated as WWT within advanced bio-refining platforms [46,47].	ARGENTINA: Dr. JP. Busalmen and co-workers from the National University of Mar del Plata (La Plata) studied treatment of high-COD effluents from potato-processing industries in MFC obtaining high COD removal, but low energetic conversion efficiency [52]. MEXICO: Researchers from the Laboratory for research on advanced processes for water treatment at UNAM (Querétaro) tested a MFC using electrodes done with low-cost graphite materials and catalysts-free. Substrate was a mixture of domestic and synthetic wastewater. Results showed competitive results against MFC using cathode platinum-catalyzed [64]. This group has tested the feasibility to obtain $bio\text{-}H_2$ from tequila vinasses but also stresses the technical difficulties to develop a full-scale process for this application [53].

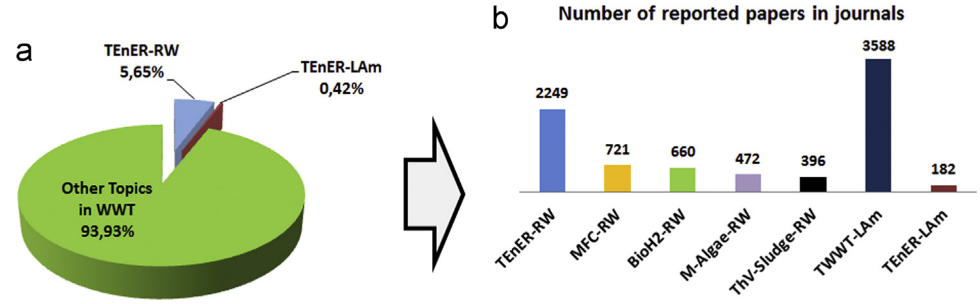

Fig. 2. World and Latin-American Research about TEnER Microbial Fuel Cell (MFC-RW), biological processes for hydrogen production (BioH2-RW), effluents remediation by micro-algae (M-Algae-RW) and thermochemical processes for sludge valorization (ThV-Sludge-RW) worldwide. Technologies for wastewater treatment (TWWT-LAm) and wastewater technologies for enhanced energy recovery in Latin-America (TEnER-Lam).

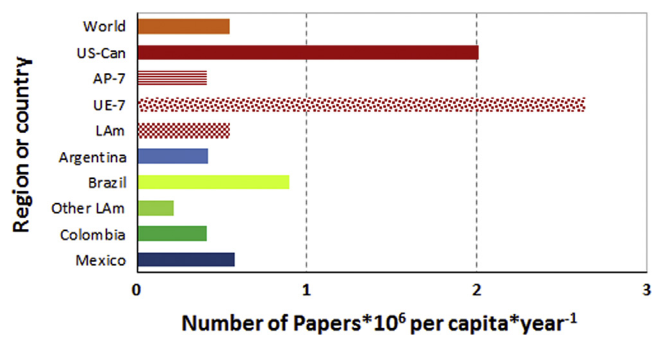

Fig. 3. Number of national and regional scientific publications per-capita on WWT Technologies data presented for European Union (UE-7) was gathered from seven countries: Belgium, France, Germany, Italy, Netherlands, Spain and United Kingdom. For the Asia-Pacific Region (AP-7) seven countries were selected: Australia, China, Japan, Malaysia, New Zealand, South Korea and Taiwan. North America (US-Can) and Latin-America (LAm) regions.

promising for enhanced production of energy in wastewater treatment applications [36–47]. Among them, microbial fuel cells (MFCs) is the most sophisticated and ambitious technology being developed, although processes involving fermentative production of biohydrogen and microalgae cultivation may be viable in the near future if they fulfill their potential in the field of agro-industrial sanitation. However, in spite of the inherent uncertainty in predicting their maturation, it is possible to foresee an imminent technological change in this sector. Some authors consider these technologies complementary, not mutually exclusive. Integration of biogas, biohydrogen and MFCs could improve energy integration and options to obtain co-products or taking part of biorefining platforms [46,47]. Table 2 sums up a number of Latin-American studies undertaken on these technologies [48–54]; thus it can be seen that current research in the region may yet to position itself on the right path towards this technological transition[1].

World research about Technologies for Enhanced Energy Recovery in Wastewater Treatment (TEnER) represents 6.07% of the scientific publications in the field of WWTs, whereas Latin-American research in this area (TEnER-LAm) only contributes with 0.42% (Fig. 2a). In fact, the total number of publications about wastewater treatment technologies in Latin-America (TWWT-LAm) is only slightly higher than publications about only TEnER in the rest of the world (TEnER-RW), (Fig. 2b). Fig. 2b also shows that MFCs and bio-hydrogen together account for 61.41% of the world scientific research effort on TEnER. Latin-America as a region is on a par with the average world research per-capita on WWTs and considerably below the European Union (UE-7) and North America (US-Can), which confirms the need in Latin-America for more diversified research in this field (Fig. 3).

On the other side, Fig. 4 presents micro-algae cultivation, coupled to wastewater decontamination, as the option more studied in Latin-America with 40.11% of scientific publications in this field. This tendency is surely fueled by the enormous availability of microscopic biodiversity in this region, waiting for commercial exploitation or by political interests pressing a higher biodiesel production. Fig. 4 also shows that Brazil and Mexico represent the vast majority of regional research in these topics (81.87%). Brazil leads regional research about transformation of anaerobic treatments to obtain hydrogen-rich biogas (biohydrogen) instead of methane-rich biogas. It is also the only Latin-American country undertaking research in the field of technologies for thermochemical valorization of sludge (ThV-Sludge). Meanwhile, Mexico is moving towards the technological breakthrough that involves MFCs and keeps its intermediate expectations behind micro-algae based processes (Fig. 4). Fig. 5 points out one relevant change in the vision of Latin-American research in this field. Mexico is a leader over many countries, including the Asia-Pacific region (AP-7) and the Unites States and Canada (US-Can), in research about TEnER versus its total research committed to wastewater technologies. Other Latin-American countries have a smaller participation of TEnER in wastewater research topics than other regions. The UE-7 contribution per-capita to the global research on TEnER is the highest worldwide and it is three times higher than that in Mexico, four times higher than Brazil and fifteen higher than the average for the Latin American region as a whole.

In view of the proved gap of Latin-American research on applications and technology for enhanced use of energy from WWTs, it is still possible that the region develops its own capacities for adaptation of technologies under conditions of integral sustainability. The basic purpose is to understand to what extent this technological adaptation may overcome the environmental impacts of the current scenario. Nevertheless, the current lack of

[1] Statistics mainly based on revisions on ISI Web of Knowledge and some selected journals of Wiley Online over the period of Jan. 2004 to Dec. 2014. Only research and review articles have been considered. English, Spanish and Portuguese publications have been considered in the accounts of the Latin-American scientific production.

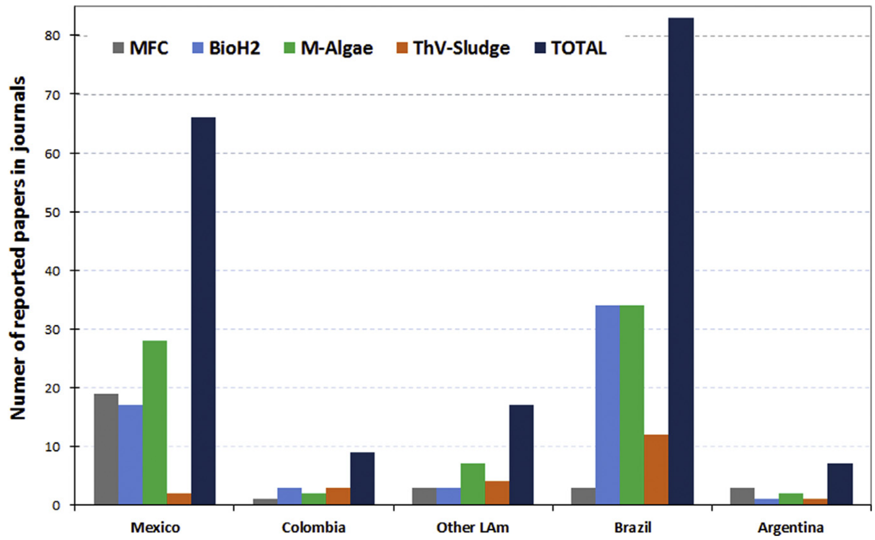

Fig. 4. Research on TEnER topics in Latin-America. Microbial Fuel Cell (MFC), biological processes for hydrogen production (BioH2), effluents remediation with micro-algae (M-Algae) and thermochemical processes for sludge valorization (ThV-Sludge).

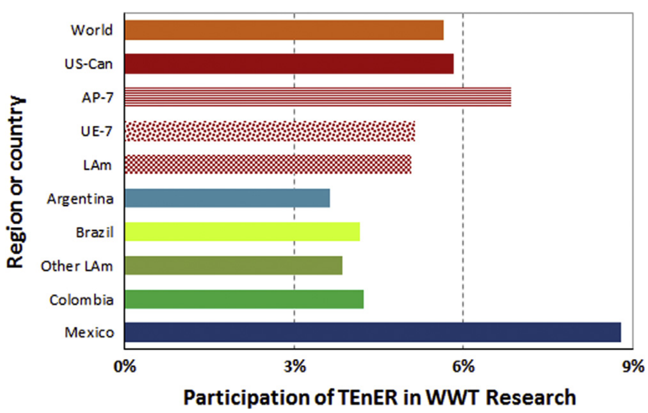

Fig. 5. Participation of TEnER in national or regional research on WWT technologies. World average (World), North America (US-Can), Asia-Pacific (AP-7), European Union (UE-7) and Latin-America (LAm) regions.

research on sustainability assessment of WWTs is of concern. This review confirms that less than 1% of the global research on wastewater treatment topics is devoted to examining the sustainability degree of TEnER. Most of these papers are based on Life Cycle Assessment (LCA) or related methodologies, and the Latin-American contribution in this field is notably small ($\sim$ 0.01%).

3.3. *Transition to wastewater technologies with energy recovery options*

Maturation of the new bioprocesses for enhanced energy production is projected for the medium-long term. Then, intermediate solutions require to be contemplated during this time of technological transition. For instance, Combined Wastewater Treatment Systems (CWWTs) are a valid alternative, with known industrial and domestic applications, which are in line with the current economic and technical status of emerging regions [55,56]. CWWTs use the biogas produced in the anaerobic primary treatment to produce energy and provide aeration in the aerobic stage. The residual thermal energy from biogas combustion is used in sludge drying operations. High-rate anaerobic processes used to treat agro-industrial effluents [16,28] could increase the energy availability of CWWTs, sufficiently to meet the energy demand of the aerobic step ($\sim$ 1 KWh/kg BOD removed). CWWTs integrate the concept of energy self-sufficiency with voluntary environmental commitment, since the quality of their end-effluents could exceed local requirements for BOD, suspended solids and dissolved nitrogen in most developing countries.

On the other hand, energy recovery from sludge should be considered during this technological transition phase, because diverse variants of the activated sludge and extended aeration processes are entering the sanitation market in Latin-America. In fact, these aerobic processes are widely recognized by their higher sludge production than anaerobic ones, and have begun to exceed the number of installed up-flow anaerobic sludge blanket (UASB) units in sewage treatment plants. This sets a historical precedent in Latin-America, where UASB had been the predominant choice for municipal sanitation for the last 20 years [57]. It is possible that a similar situation is occurring in some agro-industrial activities and sludge production exceeds the capacity for handling and end-disposal available in the region.

Availability of processes for sludge energy valorization is a pressing need because farming, composting and other techniques used in agriculture are limited by the soil's capacity to incorporate nutrients and avoid toxicological risks associated with heavy metals, salts and complex organic molecules present in some sludge [9,58]. Latin-American research regarding some advanced thermochemical processes for sludge valorization include pyrolysis, gasification and wet oxidation technologies that focuses on production of intermediate energy carriers as oils, biochar, syngas and heat. Although oils, biochar and syngas are important raw materials that link the WWTs to liquid fuels production and chemical industries [8,9], these technologies accounted as 'ThV-sludge' in Figs. 2 and 4, are not widely employed in the region. Sludge-to-biogas and incineration continue to be the predominant processes for energy production from sludge. The regional scientific interest about advanced sludge pretreatments, used to break down the sludge structure facilitating its anaerobic transformation into methane, was also explored. Technologies, such as hydrothermal and enzymatic hydrolysis, ozonation, microwave and ultrasound technologies, are perhaps out of reach or not attractive for regional research, although some of those technologies are already applied worldwide. Of particular interest has been the extraction of lipase enzymes from sludge [59] and their applications in-situ to treat anaerobically lipid-rich effluents [60,61].

Besides the technological issues, it is necessary to rethink completely the WWTs strategy focused on energy recovery in this sector. The ai-WWTs are mostly decentralized units and consequently their energy output is also decentralized, which may favor participation in natural gas networks [7], poly-generation systems feeding electrical grids closer to the end-users [62] and other energy applications including heating districts [63], and bioenergy/bio-refining platforms [46,64,65]. On the other hand, excessive isolation of small energy sources limits their options for utilization [35,62]. Future agro-industrial WWTs will require going from one bulk-effluent to one source-separated treatment strategy, in order to take advantage of effluents with bigger energy potential [65,66]. Small flows of agro-industrial effluents are more advantageous for implementation of this strategy with ancillary benefits on operational simplicity and treatment quality. However, the source-separated strategy does not rule out opportunities for energy integration or blending with other wastes in order to achieve complementary biodegradability characteristics, and to increase the energy offer by implementing centralized digestion projects [35].

4. WWTs sustainability assessment

The choice of new technologies and strategies to improve the wastewater treatment standards coupled to a major use of their produced energy should be respectful of local and global goals of sustainability. Energy from WWTs could make a difference in developing regions where energy coverage and access of the poorest communities to electricity and fuels cannot be taken for granted [23,26]. For example, there might be a choice between using a share of this energy to improve effluents' quality or to feed it into the local grid, and it could represent either the proper or the not-sustainable choice. Energy is central for water treatment, for returning it safely to the environment or for direct reuse. On the other hand, energy requirements of a non-interconnected community can tip the balance on the local development priorities. The dilemma is: how to obtain sustainable solutions through the management of this water–energy nexus?

A notable case is the industry of first-generation biofuels. Here the water–energy nexus usually has been evaluated from the perspective of fresh-water sources deterioration forced by coverage of non-fossil energy needs [12]. This industry pollutes water sources but policies regulating water uses for cultivated bioenergy and its processing are not sufficiently mature in some countries [67]. For instance, during the last decade, discharges from biodiesel industry in Colombia were controlled with a regulation

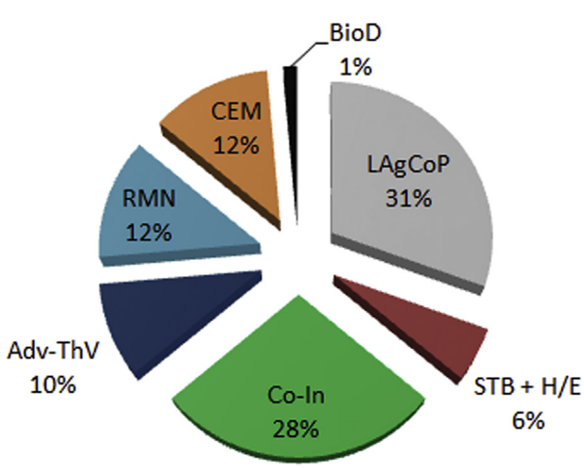

Fig. 6. Breakdown of LCA studies on sludge valorization or disposal pathways. Landfarming, agricultural and composting practices (LAgCoP), combustion–incineration technologies (Co-In), biodiesel from sludge (BioD), recovery of materials or nutrients (RMN), utilization in cement industry (CEM), advanced thermochemical processes (Adv-ThV), sludge to biogas+power or heat production (STB+H/E).

based on 80–90% of organic load removal. Consequently, typical end-discharges after treatment containing as much as 10000 mg BOD_5/L were declared compliant. The new environmental Colombian law fixes maximum limits to be met by each economic activity, being by itself an improvement [68]. Unfortunately, biodiesel production and its supply-chain, are not clearly regulated by this law, because plantations of oil palm, mills and palm oil processing plants are not always embedded in the same territory. In addition, more stringent regulations over the wastewater sector need complementary actions toward adequate environmental handling of the increased biogas and sludge production resulting from higher discharge parameters.

Energy recovered from the effluent treatment units of the palm oil industry could play a crucial role on the overall sustainability of this sector. Improvement of discharge parameters for safe reuse and participation in electrical grids might be a sustainable destination for this energy. Experiences in the Malaysian and Colombian palm oil mills have shown that replacing facultative/anaerobic ponds by covered high-rate anaerobic reactors would increase the availability of biogas for electricity to meet beyond 80% of their own demand [17,33]. Malaysian policies on renewable energy make it easier to insert this cogeneration surplus in the national electrical grid [69]; this contrasts to Colombian regulations, which block it [21,70]. In other Latin-American countries, like Argentina, Chile and Mexico new energy policies [34,71,72] promote utilization of small renewables, which eventually could favor energy projects in ai-WWTs.

4.1. Life cycle assessment (LCA) applications to WWTs

To define sustainability criteria for WWTs is an unfinished and ongoing task, that requires building consensus [18,73]. In addition, sustainability needs to be endorsed by methods specifically conceived to assess it [74,75]. Specifically, the use of LCA to assist environmental benchmarking of sanitation options has been decisive to identify priorities in the performance and planning of centralized wastewater facilities [75–78] and sanitation networks [79,80]. At the same time, LCA focused on the comparison between technologies that has been carried out for small-municipal wastewater plants [81] and industrial WWTs, particularly in the oil, chemical and tannery industries [82–84]. There are LCA applications to study water reuse alternatives and their energy implications in urban, rural and industrial environments [85–87]. Nevertheless, the main LCA application in the wastewater sector has been the comparison between different options for handling, treatment and disposal of domestic and industrial sludge, including the widest variety of technologies: sludge-to-biogas, incineration, agricultural use and others, as mentioned in numerous papers [88–108]. Fig. 6 shows the breakdown of 72 sludge valorization-disposal pathways. Landfarming, agricultural and composting practices (LAgCoP) account for 31% of cases, followed by combustion/incineration (Co-In), responsible for 28% of cases. Meanwhile Sludge-to-biogas for power or heat production (STB + H/E) represents only 6%, below of the 10% of LCA studies includes advanced thermochemical processes for energy recovery (Adv-ThV).

LCA applied to WWTs differentiates the energy valorization stages of biogas or sludge. Thus, LCA of the energy projects is referred to one functional unit or reference flow based on energy units (e.g. MJ), while LCA of WWTs is usually referred to volume or treatment capacity (e. g. 1 m^3). Fig. 7 presents the typical boundaries used in LCA studies of WWTs. Variability in the choice of the functional unit is not the only constraint of LCA applications in this field. Some limitations in the results interpretation are due to the lack of unified criteria in the choice of the environmental assessment method [109]. However, the fundamental issue is how to

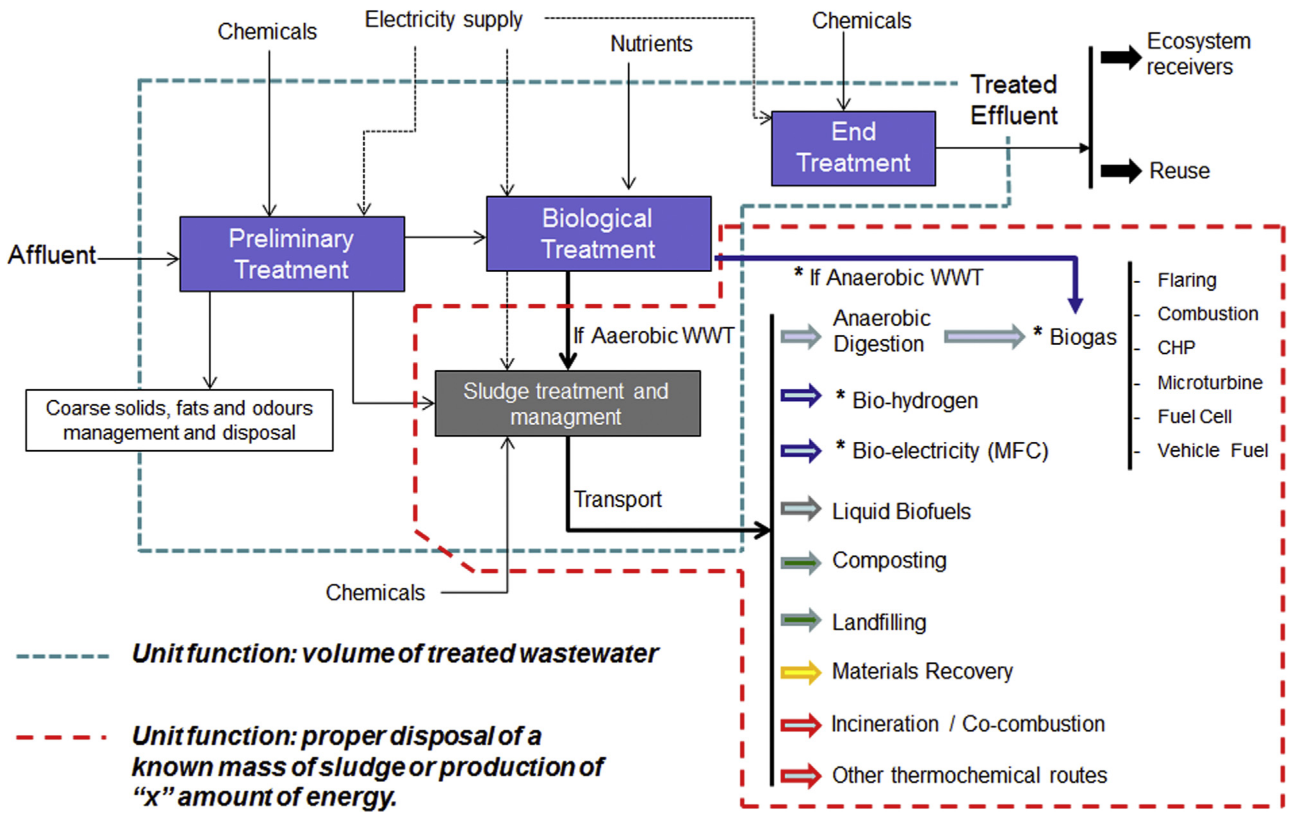

Fig. 7. Typical boundaries used in LCA studies for WWTs.

incorporate the multi-output character of these systems in the environmental evaluation, particularly when recovery of resources or energy is addressed. Effectively, WWTs can be linked to diverse energy valorization options (e.g. electricity, heat and biofuels) and effluents' treatment can be provided by different technologies (e.g. TEnER, CWWT). Each single combination would then entail a different life cycle and comparative LCA would provide systematic information to identify the best environmental-economic synergy between the wastewater and the energy generation sides. Even though different barriers and weaknesses are attributed to LCA when it is applied to WWTs, this methodology seems to be more consolidated to tackle sustainability concerns in this sector, as stated in a recent review [110].

4.2. Sustainability of agro-industrial WWTs

Once sustainability of WWTs has been analyzed under a general LCA perspective, it is possible to discuss sustainability of ai-WWTs. Sometimes, ai-WWTs have been included in the energy and environmental analysis of the full life cycle of agro-industrial supply-chains [111–113]. However, specific LCA for ai-WWTs as autonomous systems providing environmental and energy services is really scarce [114–117]. A number of studies point out that incorporation of LCA is encouraged along with application of its results or recommendations in the early stages of new bioprocesses design and renewable energy technologies, where the overall aim is to achieve sustainability in the full-scale application [65,118–120]. New high-rate anaerobic processes, MFCs as future wastewater treatment options and micro-algae for bioenergy production, coupled to remediation of agricultural effluents, have been recently examined through an emerging approach known as prospective LCA [121–123]. It is important to mark that prospective LCA regarding MFCs, generally tries to determine its environmental competitiveness compared with mature anaerobic processes regarding the wastewater treatment function. On the other hand, prospective LCA of microalgae systems stresses the impact assessment on the basis of the energy function compliance.

4.3. Sustainability criteria applicable to ai-WWTs

So far the multiple environmental indices generated by the LCA methodology have been commonly used in the sanitation sector, to establish inter-linkages with economic and social dimensions in order to obtain more complete indicators of sustainable development [79,124]. This is mainly because WWTs relationships with neighboring ecosystems and closer economic activities seem to have more environmental impact than their operation by itself, which is a characteristic of waste systems [125,126]. Efforts of the scientific community to place LCA closer to the economic and social dimensions of the sustainability notion are generalized and cover the totality of technological functions and product systems [127]. Initiatives for social life cycle assessment (SLCA) and life cycle sustainability assessment (LCSA) are being structured [128]. However, this approach continues to be carried out mainly through eco-efficiency theory and conceptual elements of the life cycle costing (LCC) approach [127–129].

On the basis of the classical approach of the LCA combined with sustainability indicators, the criteria to outline sustainability goals and policies in the wastewater sector have been the greenhouse gases control and energy savings, two criteria emphasizing the close links between wastewater treatment, energy and climate change. From this starting point, the environmental management of the water–energy nexus has evolved towards the concept of total water cycle management, being especially notable in the urban context. This principle involves and defines the participation of WWTs in the water cycle, as the key element to achieve carbon neutrality and reduce the pressure on fresh-water sources [19,130–132].

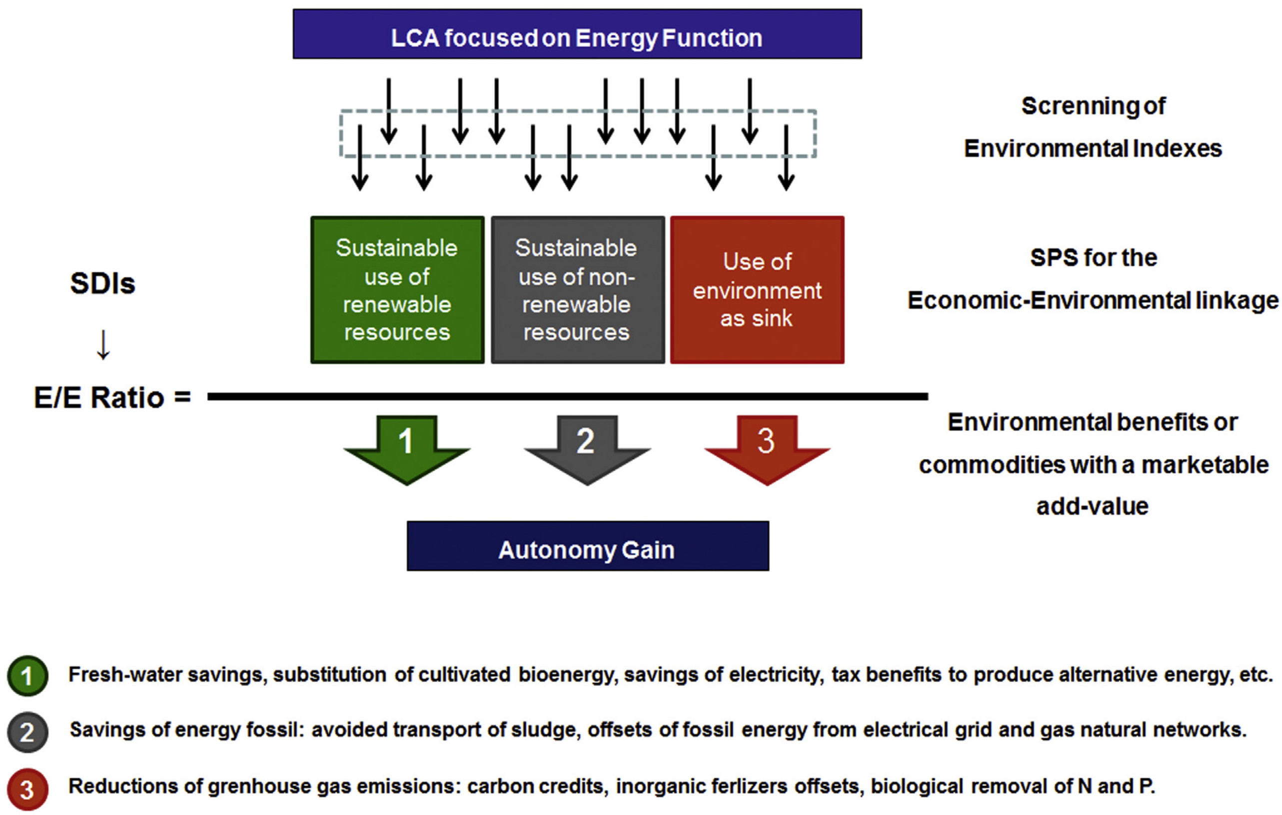

Fig. 8. Proposal of conceptual framework to improve sustainability assessment of ai-WWTs.

Complete inventories to determine the carbon footprints and potential reduction of greenhouse gases (GHG) emissions are being carried out successfully in municipal and agro-industrial sanitation activities [116,133], including for the first time, Chile and Mexico in the Latin-American region, which has put biogas from WWT in the whole national inventory of renewables and in the group of potential actions for GHG reductions [71,72]. Nonetheless, it is necessary to put more effort into bringing closer LCA to the assessment of local development goals. LCA is mainly focused on global effects (e. g. global warming), while the treated water management and produced energy may usually be associated with impact of local character (e. g. eutrophication, toxicity, non-renewable resources use, etc.) [134]. This initiative is mainly encouraged when sustainability analysis is oriented to recommend adaptable technologies for one specific context [135]. As mentioned before, the important amount of environmental indices generated by LCA might permit to establish easier linkages with the social and economic spheres of sustainability. Historically, Multi-criteria Analysis (MCA) has allowed the building of the most well-known Sustainable Development Indicators (SDIs) for municipal WWTs, generally starting with environmental indices obtained by LCA or related [124,136,137]. Nevertheless, these SDIs are not the most appropriate for ai-WWTs, because these systems are committed with two declared and recognized technological functions: environmental remediation and renewable energy production. Energy from ai-WWTs is not renewable in the strictest sense, since biogas and sludge are secondary energy carriers and its renewability requires to be analyzed from the life-cycle perspective. Methane and nitrogen inside biogas and sludge respectively are not carbon neutral, and during the wastewater treatment some addition of phosphorous, limestone and other non-renewable resources might be necessary. However, this ai-WWTs energy renewability equals, and can surpass, some proposed sustainability standards for small-bioenergy systems based on energy from crops [24], particularly because it avoids changes in land uses, does not require agrochemicals and the water–energy nexus correctly managed would aid to reduce the need of fresh-water supply for the local production system. A screening of different SDIs used to analyze small-decentralized WWTs, chemical processes, biorefining platforms and bioenergy systems [137–140], shows that the latter presents the following desirable characteristics: (i) they can be easily correlated with single environmental indicators possibly obtained by LCA, (ii) environmental-economic and environmental-social inter-linkages are related to Substantial Principles of Sustainability (SPS) inherent to the declared technological functions and (iii) well-formulated SPS avoid the handling of an excessive amount of single indicators or criteria[2].

4.4. Conceptual framework to assess sustainability of ai-WWTs

The wastewater treatment sector requires to move forward to refined and integral methodologies to assess sustainability involving a more complete identification and valuation of the technological functions performed by each type of WWTs in each location [115,141,142]. Environmental and energy functions of ai-WWTs are equally decisive to define minimum sustainability standards for these facilities and LCA can deal with that. Experience with LCA applied to study the energy supply through cultivated biogas [143,144] and biogas from solid wastes [145,146] is adaptable to analyze the water–energy nexus in ai-WWTs [117]. In addition, SPS are in some ways the first step towards obtaining more representative SDIs taking into account local priorities for sustainable development. Intrinsically SDIs responding to SPS criteria might

[2] Selective review of SDIs used for small-decentralized wastewater plants, bioenergy and biorefining platforms was done on the basis that these systems share some characteristics with ai-WWTs (e.g. energy production scale and autonomy needs).

bring a closer approach to valuation of the regional/local productivity. This is possible through economic co-benefits related to mitigation of relevant environmental impacts. Information collected by SDIs would ensure that energy savings or its production does not deteriorate the quality of the environmental services provided, particularly compliance with water quality standards.

Following this path, the eco-efficiency theory could be implemented as a consecutive or final stage to LCA in the process of tailoring SDIs to measure sustainability of ai-WWTs energy producers [129,147]. It can be seen that the economic consequences of the bioenergy, or alternative energy utilization, can foster local/regional economic competitiveness, and specifically an autonomy gain of WWTs as net economic profit. In this view, SDIs can be expressed as eco-efficiency ratios (E/E), dividing the reduction of the emissions baseline by the autonomy gain or other economic indicator selected or structured, as shown in Eq. (1). The upper term in this E/E ratio follows a similar principle used in a previous work, where LCA allowed to evaluate the indicator Net Environmental Benefit (NEB) for municipal WWTs [148]. This is similar to the Environmental Load Ratio (ELR) and other indicators currently being developed from combined emergy and life cycle approaches [142]. Thus, a proposed conceptual framework to obtain SDIs for the economic-environmental interphase of sustainability applied to ai-WWTs is summarized in Fig. 8.

$$E/E = \frac{\textit{Emissions Baseline} - \textit{Emissions for WWTs with enhanced energy production and use}}{\textit{Autonomy Gain}} \tag{1}$$

5. Outlook and conclusions

Effluents from agro-industry offer big options for enhanced energy production during their treatment and ai-WWTs are gradually engaging with this goal. This review describes the water–energy nexus present in ai-WWTs and reveals how this nexus is waiting for a more sustainable management. Emerging regions, such as Latin-America, with a considerable shortage of efficient wastewater technology to treat these effluents, are concerned about marked environmental deterioration associated with the growth of agro-industry and low competitiveness of the energy produced inside ai-WWTs, which is usually wasted.

Furthermore, there is a noticeable lack of well-harmonized environmental and energy policies to encourage a major incorporation of this kind of energy into projects committed with local goals of sustainable development. The world tendency is to develop new biotechnologies focused on enhanced energy production to be implemented in the medium-long term, taking advantage of the energy potential of agro-industrial effluents. Latin-American research is clearly involved in this technological and scientific effort mainly in applications of micro-algae cultivation with simultaneous water remediation. Mexico leads some initiatives in the field of MFCs and Brazil seems more interested in mid-point technologies, such as biohydrogen production. Forecasting the future is an uncertain task, but it could be foreseen that Latin-American research in this field will not be enough to achieve higher utilization rates of the energy produced by advanced ai-WWTs, and an important amount of technological transfer in this field will be necessary. For these reasons, it is very important to endorse the sustainability of any technological replacement, own or assisted, to be implemented to prevent major damage to local ecosystems.

This study reveals big weaknesses in the research and application of methodologies for sustainability assessment in the wastewater sector. Consequently, this paper states the need of tools to assess sustainability of ai-WWTs with the potential to implement energy valorization routes. A first approach of a novel conceptual framework to assess sustainability of these systems was outlined here based on three fundamental principles: (i) to recognize the energy production as a second technological function of ai-WWTs on a pair with the primary environmental function; (ii) to obtain environmental impact indicators by means of LCA and (iii) to facilitate the evaluation of the impact on the local needs of developing regions, by adapting some elements of the eco-efficiency theory or SPS used in the evaluation of bioenergy systems.

Finally, it is expected that this review, and subsequent contributions, will inform research focused on developing SDIs that account properly for the effect of a major energy commitment of ai-WWTs on compliance with water quality standards. This methodological approach would be useful to assist with the technological upgrade of ai-WWTs in emerging regions, under criteria of environmental compatibility and proper integration of the enhanced energy production to achieve local and global development goals.

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