

Review

# Biorefinery of Sewage Sludge: Overview of Possible Value-Added Products and Applicable Process Technologies

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**Abstract:** The disposal of excess biological sewage sludge from wastewater treatment is a growing environmental issue due to the vast quantities generated worldwide. For many years, sludge disposal has been considered an inevitable “nuisance” linked to the main task of wastewater treatment; recently, the issues relating to the presence of emerging pollutants in sludge have contributed to severe limitations on traditional disposal routes and increased process costs. As a consequence of the water industry’s approach to sustainability and circular economy principles, the investigation into options for sludge-embedded resource recovery has been increasing over time. Among these, the definition of biorefinery encompasses many processes used to process sewage sludge for biofuel and/or resource recovery. In addition to the “conventional” recovery of biogas and nutrients, biopolymers (PHAs and EPS), proteins, enzymes, biopesticides, and biofuels are among the “new” sludge extraction products that are being studied. Not all of the proposed technologies are, however, mature for industrial exploitation as yet. This paper presents an overview of possible product recovery from sludge biorefinery, with emphasis on recent developments, and on the benefits and limitations of applicable technologies for ensuring sustainability and environmental efficiency, through an analysis of the current literature.

**Keywords:** sewage sludge; biorefinery; energy; biopolymers; materials recovery; circular economy



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## 1. Introduction

Excess biological sewage sludge (EBSS) and its disposal are growing environmental issues worldwide: production is estimated at more than 13 million t/y (dry solids, DS) in Europe [1], approximately as much in the USA. [2], more than 30 million t/y in China [3], and at over 43 million t/y in India, where a large part is dumped into surface waters or land without treatment [4]. At the urban level, sewage sludge constitutes an abundant organic waste stream with per capita production estimated at 20–25 kg DS/person-y in the EU [5], second only to food waste (production estimated at 1.3 billion t/y) [6]. Due to its composition, sewage sludge could be potentially exploited as a renewable carbon source, rather than being considered an inevitable “nuisance” linked to the main task of wastewater treatment. The need for environmentally safer and more sustainable EBSS disposal routes is becoming acute due to increasing quantities and concerns related to its emerging possible pollutants content, which discourage or rule out traditional practices. EBSS, in fact, often contains pathogenic microorganisms, toxic compounds, including heavy metals, polycyclic aromatic hydrocarbons, dioxins and furans, per- and polyfluoroalkyl substances (PFASs), pharmaceutical compounds, and others [7], which remain embedded in biomass after their incomplete degradation during biological wastewater processes [8].

EBSS processing and disposal have a significant effect on the final energy and economic performance of wastewater treatment plants (WWTP), accounting for over 50% of their related burden, and contributing to almost 40% of their energy consumption and greenhouse gas emissions [9]. Sludge treatment and disposal costs vary depending on adopted methods and local conditions and have been estimated at between 160 and 310 €/t (DS)

in EU countries [10]. Disposal in agriculture has represented the most widespread reuse application since early history [11], and is still an option in some countries due to low investment costs and nutrient recycling benefits; however, increasingly stringent regulations related to pollutants transfer into soils are being introduced [12]. An alternative to soil application was traditionally represented by incineration but this route implies loss of energy and materials and potentially negative environmental impacts. Sludge requires some preliminary dewatering/drying and transportation onto fields or combustion facilities, with significant energy inputs in either case [13]. In addition to soil and crop pollutants accumulation, spreading can create environmental nuisances through the propagation of odours, insects, and pests. Incineration, on the other hand, requires stringent flue gas emission control and may find strong opposition from environmental activists; combustion residuals (incinerated sewage sludge ash (ISSA)) concentrate metals contained in the sludge and are generally disposed of in secure landfills at considerable cost, with the risk of inducing further environmental contamination. The prevalent current challenge in WWTP waste management, in addition to the reduction in these impacts, has been identified in the recovery of energy and materials, by implementing EBSS-centred circular economy schemes that could provide greater added value than traditional disposal methods.

According to current legislation (European Directives 91/271/EEC and 86/278/EEC), EBSS, whether treated or untreated, is defined as a residual product, hence as “waste”, classified in the European Waste Catalogue (EWC) with code number 190,805 [14]. The Waste Framework Directive (2008/98/EC) specifically introduces the “end-of-waste” concept, whereby end products are no longer considered waste upon the fulfilment of four conditions: their use for specific purposes; the existence of a market for the product; the existence of technical requirements and standards for products; and the proof of no adverse environmental/health effects induced by their use. Upon fulfilment of these prerequisites, sludge could then become a valuable secondary raw material on its own. Compliance with these conditions can be ascertained on a case-by-case basis for some specific final uses.

In 2021, the European Commission closed its public consultations on the planned Sewage Sludge Directive (SSD): in circulated drafts, it is stated that *“the reuse of sewage sludge should contribute to the exploitation of the value in water, unlocking the full potential of opening up markets for reused sewage sludge opportunities and raw materials embedded in it”* [15]. This would create a pivotal paradigmatic shift in the status of sewage sludge since it would permanently move from its current “waste status” to the condition of a valuable by-product of the wastewater treatment cycle. This concept is closely related to the new paradigm that is being currently introduced in WWTP planning and design, moving from the traditional concept of ‘treatment’ to the new function of the water resource recovery facility (WRRF). The new definition clearly states the dual purpose of these facilities to a) protect the environment from pollution and, at the same time, b) recover water [16], nutrients [17], and energy [18] to reduce the environmental impact and enhance the sustainability of the urban water cycle.

Several existing or potential options for EBSS-embedded resource recovery have been investigated, ranging from biological process innovation, new thermochemical technologies, the integration of bioelectrochemical processing, biorefinery, and others. Traditional recoverable resources, such as biogas from sludge fermentation [19], are now complemented by liquid and solid energy end products (e.g., biodiesel and biochar) [20], and nutrients [21]. The possibility of recovering other high-value-added products, such as polyhydroxyalkanoates (PHAs), extracellular polymeric substances (EPS), and others, is also intensively investigated [22,23]. All of these process technologies can be grouped under the definition of “biorefinery”.

This paper presents a state-of-the-art review of the current literature on sludge resource recovery possibilities from biorefinery chains, with emphasis on recent developments, as well as on the benefits and limitations of applicable technologies for ensuring sustainability and environmental efficiency. Such technology review, comprehensive but not specific,

could orient readers in outlining possible alternatives for the implementation of highly efficient biorefinery schemes.

## 2. Sewage Sludge Characteristics

Raw sewage sludge could be defined as a multiphase medium containing organic and inorganic particles, microbial biomass aggregates, and extracellular polymeric substances (EPSs), all suspended within a predominant volume of water. Originally dissolved wastewater components, such as organics (i.e., chemical energy) and nutrients, are concentrated in biomass, which, therefore, contains (in terms of dry matter) an equivalent energy comparable to that of lignite, about 11–22 MJ/kg [24], and stoichiometric or superstoichiometric amounts of P and N. Sewage sludge is qualitatively characterized by three main classes of parameters: physical, relating to its structure and suitability to mechanical processing; chemical, relating to the presence of complex organics, nutrients, and toxic/dangerous compounds; biological, relating to the microbial composition, mainly concerning the presence of pathogens. The composition and type of raw wastewater and the type of biological treatment processes determine the final properties of EBSS; therefore, the variability in sludge characteristics according to location and time (even for the same location) can be quite high. Table 1 summarizes typical values for the chemical–physical characteristics of urban primary and activated (secondary) sludge that are normally monitored at WWTPs.

**Table 1.** Characteristics of two different types of sludge (primary and activated) (data from [25]).

Parameter	Primary Sludge	Activated Sludge
Total dry solids (total solids, TS) %	5–9	0.8–1.2
Volatile solids, vs. (%TS)	60–80	59–68
Nitrogen (%TS)	1.5–4	2.4–5.0
Phosphorus (%TS)	0.8–2.8	0.5–0.7
Potash (K <sub>2</sub> O %TS)	0–1	0.5–0.7
Cellulose (%TS)	8–15	7–9.7
Iron (Fe g/kg)	2–4	–
Silica (SiO <sub>2</sub> %TS)	15–20	–
pH	5.0–8.0	6.5–8.0
Grease and fats (%TS)	7–35	5–12
Protein (%TS)	20–30	32–41
Alkalinity (mg/L as CaCO <sub>3</sub> )	500–1500	580–1100
Organic acids (mg/L as acetate)	200–2000	1100–1700
Energy content (kJ/kg TS)	23,000–29,000	19,000–23,000

In addition to the “conventional” parameters reported in the table, more specific chemical characterization is needed for each sludge disposal option according to applicable regulations, which may exist at the supernational (e.g., European Union), national, and local (regional, county, etc.) levels [26–28]. Many pollutants that are originally present in wastewater could go undegraded or only partly degraded in WWTPs and may end up entrapped or adsorbed in sludge cells or flocs. These include inorganic compounds (silicates, aluminates, and calcium and magnesium compounds), toxic pollutants, such as heavy metals (Zn, Pb, Cu, Cr, Ni, Cd, Hg, and As) [29], dioxins, pesticides, nanomaterials, microplastics [30,31], and a long list of over 70 emerging pollutants including personal care and pharmaceutical products (PPCP), hormones and endocrine disrupters [32], per- and polyfluoroalkyl substances (PFASs), linear alkylbenzene sulfonate (LAS), alkylphenols (APs), phthalates (PAEs), polycyclic aromatic hydrocarbons (PAHs), and polychlorobiphenyls (PCBs) [33] with concentrations ranging from <1 mg to several g per kg [34]. Pathogens and other microbiological pollutants are also present in sludge [35].

Sludge mass consists of approximately 60% (DS) biodegradable, nontoxic organic C compounds; TKN and P fractions follow in lower percentages. Volatile solid content is usually in the range of 65–77 g/L; dry matter may vary between 7–12 g/L. The sludge organic fraction is mainly composed of EPS, negatively charged polymers with high molecular

weight originating from microbial cell secretions and lysis. EPS contains most of the sludge proteins, nucleic acids, humic substances, polysaccharides, and lipids; these comprise about 20% of the total EPS mass [36]. EPS forms a complex structure with biological cells, interlocking high amounts of humidity in flocs, and protecting them against dewatering. The presence of EPS manifests itself in the accumulation of large amounts of positively charged ions within flocs. This generates an osmotic gradient that affects the effectiveness of dewatering processes, and the sludge's rheologic behaviour [37]. In particular, granular sludge (GS) formation (either from aerobic or anaerobic processes, i.e., activated granular sludge, anaerobic sludge blanket, or anammox) is strongly affected by the presence of EPS. EPS is found in much higher amounts in granulated sludge than in any other biomass aggregation (e.g., activated sludge flocs) [38]: depending on the nature of GS granules (aerobic, anaerobic, and anammox) EPS content may vary between approximately 30 and 600 mg/g [39]. Due to its constituents, EPS is one of the most attractive and studied sludge components at the moment, given the high possibility for the sustainable recovery of novel raw materials through its biorefinery processing.

### 3. Principles of Biorefinery

Biorefinery is not an entirely novel concept of this century: traditional bioconversion processes, i.e., in the sugar, starch, pulp, paper, and vegetable oil industries that have been around for a long time can also be classified as belonging to the biorefinery concept [40]. Nowadays, the common definition of biorefinery refers more specifically to a process or a chain of processes capable of producing a broad spectrum of value-added products, such as biochemicals or biofuels, from a single feedstock or combinations thereof. Hence, biorefinery converts biomass (animal, crop, or waste) to chemicals, energy, and materials, replacing nonrenewable energy or chemical products of fossil origin. Biomass is, by definition, renewable, since plants naturally synthesize organic matter from environmentally available CO<sub>2</sub>, H<sub>2</sub>O, and solar energy. Organic waste streams from anthropic activity also contain embedded energy and materials that can be similarly recovered and exploited. The sustainable harvesting and processing of natural and waste biomasses does not negatively affect the environment, and could be carbon neutral in most cases. Therefore, biorefinery plays a key role in ensuring the closure of the cycle of biomass production and consumption, while satisfying society's need for energy and chemicals. At the moment, different biorefinery concepts have been developed, and are at different stages of technology maturity (expressed as technology readiness level (TRL)), as indicated in Table 2 [41].

**Table 2.** Feedstocks and TRL of existing biorefinery concepts.

Biorefinery Concept	Feedstock	TRL *
Conventional biorefinery	Starch and sugar crops, wood	9
Whole crop biorefinery	Whole crop (including straw) cereals	7–8
Oleochemical biorefinery	Oil crops	7–9
Lignocellulosic biorefinery	Lignocellulosic-rich biomass (wood, straw, etc.)	6–8
Green biorefineries	Wet biomass: green crops, leaves, food and organic waste	5–7
Marine biorefineries	Aquatic biomass: micro- and macroalgae	5–6

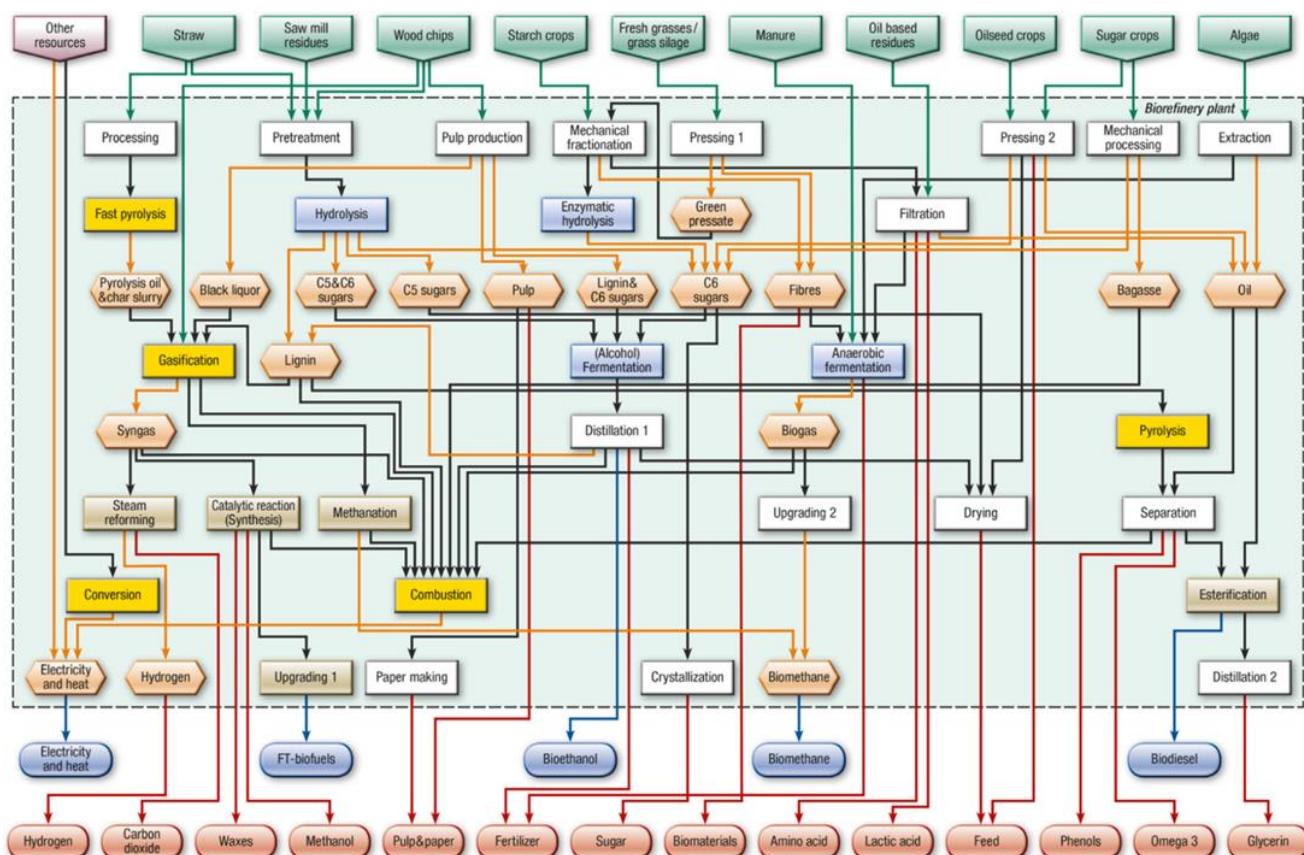
Note: \* TRL: Technological Readiness Level (according to HORIZON 2020–WORK PROGRAMME 2014–2015).

The original definition of biorefinery is given by the International Energy Agency (IEA) as: “the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, and materials) and bioenergy (biofuels, power, and/or heat)” [41]. This concept includes a wide range of technologies and processes used to break down biomass feedstock into their building blocks (carbohydrates, proteins, etc.) and convert them to different value-added products, such as biofuels or chemicals. The process is similar to the one occurring in oil refineries, which crack oil into different products; however, due to the renewable character of its feedstocks, biorefinery does not exhaust finite resources and can mitigate greenhouse gases (GHG) emissions while contributing to satisfying the ever-increasing demand for energy, fuels, chemicals, and materials.

IEA's biorefinery classification considers four main features to describe these systems:

1. Platforms: the intermediates that connect different biorefinery systems to their processes. The number of involved platforms is an indication of system complexity;
2. Products: the many possible final outcomes of biorefinery. Two possible product groups are energy (e.g., bioethanol, biodiesel, synthetic biofuels, etc.) and material products (e.g., chemicals, materials, food, and feed);
3. Feedstocks: the starting materials on which biorefinery is based. They can be grouped as either energy crops from agriculture and forestry, biomass residues from agriculture, forestry, trade, and industry, or specific organic waste streams. The latter includes sewage sludge;
4. Conversion processes: the main four process groups include biochemical (e.g., fermentation and enzymatic), thermochemical (e.g., gasification and pyrolysis), chemical (e.g., acid hydrolysis, synthesis, and esterification), and mechanical processes (e.g., fractionation, pressing, and size reduction).

A conceptual scheme (Figure 1) describing the most promising existing and developing biorefinery pathways, from feedstock to products, considering common platforms and available processes were drawn by Cherubini et al. [42]. This scheme gives an actual picture of the potential complexity of real biorefinery systems. It also provides a summary of current technology, and additional platforms, product groups, and processes may be added to the scheme represented according to the outcomes of ongoing and future research and development activities.



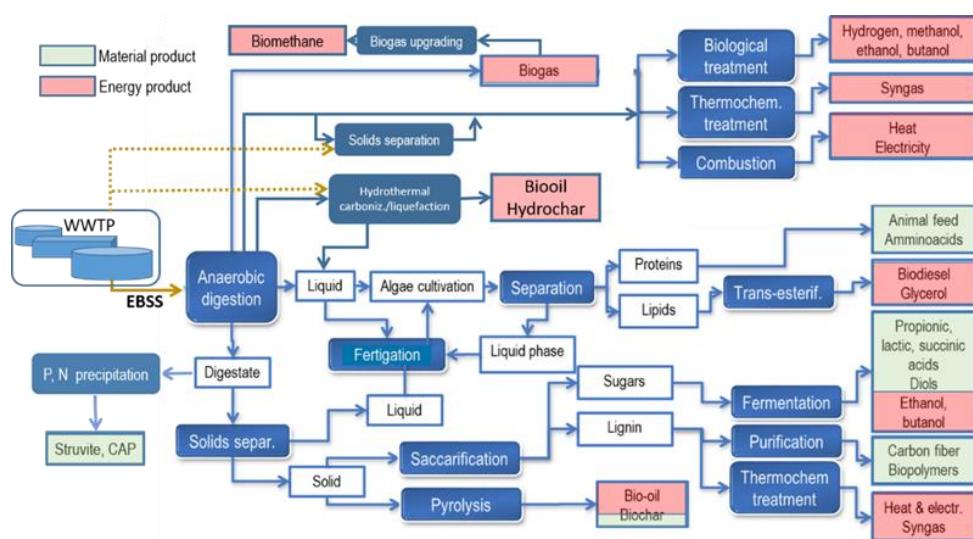
**Figure 1.** Conceptual scheme describing the relationships between the most promising existing and developing individual biorefinery systems (Adapted with permission from Ref. [42]. 2009, John Wiley & Sons).

Feedstocks can be specifically produced for biorefinery applications by photosynthesis, as in the case of land crops and microalgae, or can be the final product of a complex series of processes (i.e., wastewater treatment or food production, distribution, and wastage). The potential of waste biorefineries is also recognized in developing countries as a solution to current waste disposal issues and as a means to produce fuel, power, heat, and value-added products [43]. Lately, innovative mixotrophic wastewater treatment based on a consortium of microalgae and bacteria were introduced to exploit the different efficiencies of the microorganisms involved in removing wastewater pollutants [44,45]. All of these residuals are ideally suited as biorefinery feedstocks [46,47]. The initial rationale for the development of biorefinery was to replace fossil sources with fuels derived from cultivated biomasses [48]. The production of value-added chemicals from nutritional crop feedstock, however, directly competed with human and animal consumption, undermining food security at the global level [49]. Nowadays, biorefinery based on third-generation feedstock (i.e., GHG-neutral and non-food) has extended its scope to many other interesting applications, such as the production of feed and nutritional products, or co-bioproducts of industrial interest as substitutes for traditional raw materials. The integration of green chemistry (chemical processes free of hazardous substances) and the application of low-impact technologies into biorefinery design can help establish sustainable production chains of high-value substances. An important aspect of the biorefinery process is the continuous, consistent, and regular feedstock supply allowing facilities to operate without interruption; to achieve such continuity, various streams can be combined according to seasonal availability. Due to its continuous production cycle, sewage sludge fulfills this requirement both as a sole feedstock or as co-feedstock; biorefinery, therefore, may become an important approach in exploiting the sewage sludge-embedded resources as part of the circular economy.

#### 4. Sewage Sludge Biorefinery

According to the previous definition, biorefinery encompasses any technology used to process EBSS for biofuel and/or resource recovery: proper process integration can contribute to generating multiple possible final products (energy and/or materials), as schematically shown in Figure 2. Process integration could ensure flexibility and operational optimization in view of possible changes in sewage sludge quantities, composition, and characteristics in time. Ideally, treatment processes or operational adjustments could be introduced in WWTPs themselves, in order to improve EBSS characteristics to enhance their recovery options. Since the chemical composition and energy content of sludge vary according to sludge stream and type (e.g., primary, secondary, or mixed sludge, conventional activated sludge, MBR or EBPR sludge, or GS), these streams could be separately processed, aiming at specific final products. For example, as mentioned earlier, GS presents a higher EPS content than CAS, and primary sludge has a higher content of free fatty acids than secondary.

Some of the processes shown in Figure 2 have been traditionally adopted as sludge management practices for many years, and have been amply described in the literature. For example, the anaerobic digestion (AD) of excess sludge was introduced in its earliest form in 1885, at the Exeter (UK) WWTP, and has been constantly improved since. AD for the production of methane-rich biogas is an early example and current staple process combining resource recovery and organic matter stabilization. AD is not limited to feedstocks such as sewage sludge and manure but can include the co-digestion of organic fraction of municipal solid waste (OFMSW), food waste, energy crops, and crop biomasses residuals, as well as agroindustrial and chemical industry wastewaters. While biogas can contribute to the energy requirements of WWTPs, its economic added value is limited compared to that of other higher-value end products that could be alternatively obtained. While the sequence of biorefinery processes can be optimized to exploit the most valuable or desirable end products, AD could still remain an important step within many biorefinery schemes.



**Figure 2.** Possible biorefinery full-cycle implementation from EBSS feedstock.

Even if thermochemical combustion processes could be considered the final steps of sludge biorefinery, they will not be discussed specifically in this review. These are traditionally well-known and have been reviewed recently by several authors [50–53]; pyrolysis and gasification have also been amply reviewed [54–56]. This review of sludge biorefinery techniques focuses on recent approaches aimed at the direct recovery of fermentation products, such as organic acids, alcohols, and hydrogen, or at their postprocessing for the recovery of industrially valuable molecules, such as PHAs and VFAs, or bioproducts.

#### 4.1. Raw Chemicals Recovery from EBSS

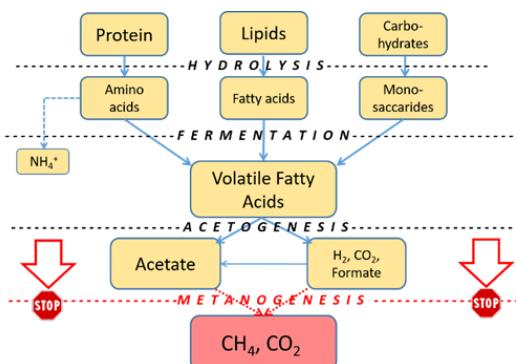
Many studies have been published on the physical–chemical characterization of sewage sludge with regard to its final disposal: a Google Scholar search (conducted on 25 August 2022) yielded around 28,000 hits with the keywords “sewage sludge characterization for thermochemical processes” (over 6000 of which were published before the year 2000) and almost 99,000 with the keywords “sewage sludge characterization for land application”. The literature on EBSS characterization for biorefinery purposes is more recent: a search with the keyword “sewage sludge characterization for biorefinery” returned just 90 results prior to the year 2000 and just over 20,000 until the present. This indicates that biorefinery has received a lot of interest in the scientific and industrial communities in the past 20 years.

Thermochemical processes (incineration, pyrolysis, and gasification) can recover heat, oil, gas, or char from EBSS, but they also destroy valuable organic macromolecules, polymers, or enzymes contained therein: three major biochemical families (carbohydrates, proteins, and lipids) represent approximately 80% of the organic matter in sludge, mostly in the form of extracellular polymeric substances (EPS). Biorefinery can address the recovery of those components, following a “pyramidal approach” in which the extraction of the most valuable constituents has the greatest priority.

##### 4.1.1. Central Role of Anaerobic Fermentation in EBSS Exploitation

AD (fermentation) is currently considered one of the most efficient solutions for managing large amounts of organic substrates, including EBSS, food, and agricultural biomass wastes. Most process chains aimed at producing high-value end products from low or negative-value feedstocks are based on this initial step. The process reduces their volume and allows the production of valuable methane (or possibly hydrogen); these renewable fuels (from sludge and other sources) are expected to contribute to the EU renewable energy portfolio in the coming years [57]. The first intermediates of the AD process are short-chain organic acids and alcohols: short-chain fatty acids (SCVFAs) are

volatile fatty acids (VFAs and carboxylic acids) with 2–5 C atoms; acetate, propionate, butyrate, and lactate are usually referred to as carboxylates. These industrial raw materials are normally produced from fossil sources but can be generated through the fermentation of organic matter following the inhibition of the conversion step of organic acids to CH<sub>4</sub> and CO<sub>2</sub> and the minimization of molecular hydrogen production (Figure 3).



**Figure 3.** Anaerobic fermentation steps. By suppressing methanogenesis, VFAs and hydrogen could be recovered from the process.

Ample literature on feedstock pretreatment for biogas production enhancement in AD exists; however, there is little specifically concerning VFA production potential. SCVFA production rates from the AD of EBSS are often limited by slow hydrolysis and poor substrate availability. Hydrolysis enhancement can increase production rates: Li et al. [58] observed that SCVFA production increased 3.7 times by 1.8 mg/L of HNO<sub>2</sub> sludge treatment prior to AD; Zhang et al. [59] observed that pretreating EBSS with 176.5 mg/L of NH<sub>3</sub> increased VFA concentrations to 267.2 mgCOD/gvss. Liu et al. [60] applied heat-CaO<sub>2</sub> thermal hydrolysis pretreatment (67.4 °C and 0.12 g/gvss) to sludge, increasing the fraction of biodegradable organic matter and achieving maximum VFA concentrations of 336.5 mgCOD/gvss. The methanation rate is significantly reduced by acid accumulation in the digester [61]; therefore, it is evident that proper fermentation control is essential for successful VFA recovery from AD processes.

Due to their characteristics of high flexibility, low stiffness and brittleness, high tensile strength and toughness, VFAs are highly valuable in the bioplastics and biotextiles production processes; acetate and butyrate are starting blocks for polyhydroxybutyrate (PHB) production, propionate for polyhydroxyvalerate (PHV) production [62]. VFAs, as such, are unsuitable as fuels due to their high O:C ratio (in the range 1:1–2:5) and low energy density; however, they can serve as raw materials for liquid biofuels synthesis: acetate, for example, is a precursor of fuel alcohol that is blended with gasoline [63]. The benefits of AD's VFA production should be carefully evaluated compared to those from biogas recovery [64]. Apart from the high commercial value of the produced VFAs, these also have reuse potential within the same WWTP as an internal carbon source in biological nutrient removal, instead of external sources such as acetate and methanol [65].

Fermentation within the VFA platform originates a mixture of short-chain carboxylates that, after concentration by nanofiltration membranes, liquid extraction, or anion exchange [66], undergoes secondary bioconversion to yield medium-chain fatty acids (MCFAs, i.e., carboxylic acids with C atoms in the range of 6 to 12). Due to their properties, MCFAs are considered more valuable chemicals than SCVFAs. Compared to SCVFAs, characterized by a high O:C ratio, MCFAs (with lower O:C ratios, between 1:3–1:6) feature higher energy densities (approximately 3500–4800 KJ/mol) and serve as biofuel precursors or raw materials for various commercial products, such as fragrances, food additives, antimicrobial agents, and others [67].

Formate ( $\text{COOH}^-$ ) can be consumed as the sole carbon source by formotrophic microbes: it can be thus converted into an ample array of final products, including fuels, solvents, plastic monomers, pigments, and even protein meal for food or animal feed, creating the basis of an entire formate-centred Circular Bioeconomy [68]. Due to their value, the optimization of acetic and formic acid production is a research hotspot in the AD field: formate generation via VFA degradation by acetogenic microbes is limited by thermodynamics, while it is easier for acidogens to directly metabolize organic matter into these forms. Factors such as pH, ORP, and initial C/N ratio are known to affect the production of acetic and formic acids. Optimal conditions occur at pH 7.0 and low ORP ( $-450 \text{ mV}$ ): Wang et al. [69] indicated that neutral pH could provide a suitable niche for *Petrimonas*, *Trichococcus*, and other diverse acetic/formic acid-producing bacteria.

Biogas, the most common final AD product, is a valuable energy product, consisting of approximately 40–75%  $\text{CH}_4$  and 25–60%  $\text{CO}_2$ , plus other minor components ( $\text{H}_2\text{S}$ ,  $\text{NH}_3$ , siloxanes, etc.) depending on the feedstock. Biogas is suitable for upgrade strategies (biomethanation) to generate a fuel product compatible with natural gas standards [57]; however, biogas bioconversion into biopolymers such as polyhydroxyalkanoates (PHA), protein, or ectoine has emerged as a promising alternative approach [70]. Biogas was tested for the industrial production of polyhydroxybutyrate (PHB), a specific short-chain, biodegradable, and biocompatible PHA thermoplastic synthesized by methanotrophs (methane oxidising bacteria (MOBs)) from C1 carbon sources ( $\text{CO}_2$  and  $\text{CH}_4$ ), under growth limiting conditions [71].

The major constraints associated with  $\text{CH}_4$ /biogas bioconversion technologies are represented by the limited mass transfer rates of  $\text{O}_2$  and  $\text{CH}_4$  ( $1.3 \times 10^{-3}$  and  $1.4 \times 10^{-3} \text{ M/atm}$ , respectively) [72]. This requires the development of highly efficient turbulent contactors to support enhanced methane transformation even in the presence of unfavourable values of Henry's law coefficients [73]. For this reason, notwithstanding this potential, long-term continuous operation of biogas-to-PHB production processes have not been yet reported [74].

#### 4.1.2. Biopolymers

Polyhydroxyalkanoates are biodegradable polymers internally accumulated by microorganisms as energy and carbon storage reserves, generally under nutrient imbalance conditions during biological wastewater treatment. PHAs made up of monomeric units of (R)-3-hydroxyalkanoic acids accumulate as granules inside microbial cells in variable proportions, from 1 to 90% of cell dry weight. More than 150 monomeric units of PHA have been identified so far: poly-beta-hydroxybutyric acid and its co-polymer poly (3-hydroxybutyrate-co-hydroxyvalerate [ $\text{P}(3\text{HB}-\text{co}-\text{HV})$ ]) are among the most common. These molecules exhibit properties comparable to those of petroleum-based plastics, hence their use as a biodegradable and biocompatible conventional plastic substitute could reduce environmental and human health problems related to nondegradable petrochemically derived materials. PHAs may also serve as feedstock for biofuel (3-hydroxybutyrate methyl ester (HAME)) production, or for the production of specific chemicals such as acrylate and propene [75,76].

PHA has been extensively studied and characterized in terms of properties and possible industrial applications; however, their cost is still higher (up to 6 fold) than fossil-derived plastics [77], since industrial processes for their production are mostly based on pure microbial cultures and expensive substrates such as glucose, fructose, and propionic acid, hindering their commercial appeal so far. More cost-effective production technologies, using wastes and/or industrial by-product streams as raw materials for PHA production could decrease overall production costs by up to 50% [78]. Low-value substrates, such as EBSS, and the use of microbial mixed cultures could also allow energy (no sterilization required) and fermentation (less expensive reactor construction) cost reduction and control equipment minimization, with the possibility of efficiently integrating this technology in traditional WWTPs [79]. Preferred substrates for PHA synthesis are butyrate, lactate, and,

to a lesser extent, acetate—all major products of primary fermentation within the VFA platform [80].

As pointed out by Valentino et al. [81], PHA extraction could also be advantageous for final sludge disposal optimization: separately fermented primary sludge could be minimized by the conversion of organics into VFAs, which would favour subsequent internal PHA accumulation in EBSS since PHA-storing bacteria feed on VFAs from the liquid phase and accumulate them intracellularly as biopolymers. In enhanced biological phosphorus removal (EBPR) systems, for example, substrate VFA production is encouraged, so that phosphate-accumulating organisms (PAOs) can synthesise and intracellularly accumulate PHAs under anaerobic conditions, allowing them to perform alternate P accumulation and release. Glycogen-accumulating organisms (GAOs) are a second group of bacteria responsible for PHA accumulation under anaerobic conditions. Microbiological PHA production, therefore, implies favouring the selective growth of PHA-storing bacteria (PAOs or GAOs) by exerting dynamic substrate feeding conditions (“feast and famine” cycles, i.e., alternating conditions of C availability and unavailability) [82,83]. During the “feast” phase, ammonia and carbon are assimilated by microorganisms, which synthesise PHA. After substrate exhaustion (“famine”), stored PHAs are consumed along with external ammonia. Process optimization leads to the development of mixed bacterial cultures with significant PHA storage capacity, up to 65% of cell content [84]; however, insufficient process stability was reported [85]. PHA accumulation has been observed in the range of 0.30 to 22.7 mg polymer/g sludge, depending on process conditions [86,87]. While many approaches based on mixed-culture processes have been proposed, none have been implemented at the industrial scale, so far. The most successful approaches for PHA extraction from biomass so far are based on alkaline fermentation [6,88].

In contrast to intracellular PHA needing a specific extraction process, high-value EPS macromolecular cellular components are released by cell lysis or excreted across cell membranes into solution, and typically remain trapped in the intracellular spaces of microbial aggregates. Unless recovered, EPS are discarded with the effluent or returned to the biological units after sludge processing. EPS recovery could further shift treatment processes to zero-waste discharge, minimising the final organic load output of WWTPs by recovering materials in production processes.

Granular sludge-derived EPS demonstrated hydrating properties and gel-forming capacities similar to alginates; therefore, several biotechnical uses of EPS exist in the food, paints, oil drilling ‘muds’, cosmetics, and pharmaceutical industries. EPS may have potential uses as biosurfactants in tertiary oil production, biological glues, and as a component of biofilm systems; due to its viscous properties, it is used to increase the viscosity of technical materials and food preparations, with another still unexplored biotechnological potential, including medical applications [89]. EPS coatings improve the self-extinguishing properties of fabrics due to their content of phosphates which improves flame retardation [90]. Pollutant adsorption by EPS has been studied. The presence of functional groups such as carboxyl, phosphoric, sulfhydryl, phenolic, and hydroxyl groups in EPS can complex heavy metals, hence EPSs have been proposed for metals removals: for example, EPS from *Bacillus megaterium* was tested for Cu removal, while other bacterial EPS types exhibited high affinity for Cd [91,92]. EPS also adsorbs organic pollutants: Spath et al. [93] reported adsorption of solute BTX greater than 60%; the adsorptions of phenanthrene [94], humic acids [95], and dyes [96] were also reported. In fact, only a small fraction of pollutants in biological mixed liquor is actually adsorbed within bacterial cells themselves: since EPS is always negatively charged, it binds with positively charged organic pollutants by strong electrostatic interaction. Furthermore, soluble EPS contains a higher protein fraction than bound EPS; since proteins have higher binding capacities than humic substances, soluble EPS captures most of the pollutants [95].

EPS is involved in most biofouling occurrences in WWTPs, allowing the formation and persistence of microbial aggregates on exposed surfaces such as heat exchangers, piping, and membrane media. Biological sludge EPS accounts for 10–40% of sludge dry weight,

with 75–89% of its extracellular organic carbon consisting of proteins and saccharides; hence, it could serve as a C or energy source in conditions of substrate shortage [97]. The quantity of EPS generated varies according to the biological process: it was estimated that a UASB facility of 100,000 P.E. capacity could yield 150 kg-EPS/d [98], while an anammox unit of the same capacity could generate up to 185 kg-EPS/d [99].

Techniques for EPS extraction include physical, chemical, and biological approaches: physical treatments include centrifugation [60], sonication [100], electroporation [101,102], blending [103], and heating [104]. Chemical extraction involves the use of cation exchange resins [105], or of alkaline, acid, or aldehydic reagents and organic solvents (ethylenediamine tetraacetic acid and formaldehyde plus NaOH) [60,106,107]; finally, the biological method includes enzymatic treatment [108]. Bound and soluble EPS fractions can be separated from sludge cells by centrifugation: the former remains attached to solids while the latter is recovered with the centrate. Physical (ultrasonication and heating) and chemical methods have proven effective in recovering bound EPS from most types of sludge. EPS final composition largely depends on adopted extraction methods, which can result in significant yield and quality (properties and functional groups) variations in the extracted exopolymers, affecting their exploitation. However, common extraction and recovery methods have rarely been evaluated in detail so far in terms of the suitability of recovered EPS for specific practical applications. Discussion is still ongoing between researchers recommending cell lysis minimization techniques, and those advocating heavy cell integrity destruction for the extraction of different, novel biopolymers [104,106]. These aspects need further research to optimize EPS recovery and reuse.

#### 4.1.3. Proteins

Proteins are essential components of animal feed, and their recovery from EBSS could offer various benefits over traditional sources: the high fraction of proteins (~50% dry weight) in sludge makes it a highly suitable source for their recovery; therefore, this is a well-studied waste-to-resource approach. Currently, two patented technologies for protein recovery from sludge are applied in practice [109,110]. Recovered sludge-derived proteins find industrial uses as fertilizers, adhesives [111], fire-extinguishing foam [112], or animal feedstuff [113]. Efficient protein recovery and reuse methods depend on sludge type, nature of pretreatment, and separation and purification methods since all of these factors can modify protein properties (e.g., molecular weight, conformation, type, etc.) [114].

The dissolution of bacterial cell walls and release of bound EPS, and the disruption of intracellular materials (cytoplasm) are critical prerequisites in order to release soluble proteins into the bulk liquid. Physical, thermal, chemical, and biological processes and combinations thereof have been proposed: these include ultrasonication, microwaves, electric pulse, deflaking, and thermal decomposition. Oxidative cell destruction by hydroxyl radical generation has been reported as effective for protein solubilisation, but high oxidant dosages may lead to their undesired mineralisation. Ozonation was indicated as an effective and environmentally-friendly chemical technique for protein solubilisation [114]. Biological pretreatment by the addition of enzymes, or specific enzyme-producing microbes, is considered attractive compared to chemical or physical methods for the solubilisation of sludge proteins since it is considered more environmental-friendly, does not introduce external chemicals in the process, and does not require special equipment. Studies, however, reported that enzyme (e.g., protease and lipase) addition could cause protein degradation into polypeptides and amino acids [115].

Intracellular protein recovery was achieved by sludge disintegration using alkali treatment coupled with ultra-sonication [113] or combined enzymatic methods consisting of disintegration by enzyme, acid, and base hydrolyzation processes followed by isoelectric precipitation, centrifugation, and freeze-drying [116]. Protein extraction yields up to 80%, with a composition comparable to commercial protein feeds, have been achieved, with most of the metals initially present in the sludge being removed from the final products. A coupling of chemical and biological methods was shown to increase the solute concentration

of protein: the former (with a dosage of ethylenediamine tetraacetic acid (EDTA), SDS, formaldehyde, and NaOH) aids the release of trapped EPS and the disintegration of cell walls; the latter degrades released organics enhancing protein accumulation [117].

A proper comparison of all possible methods available for protein recovery in view of their circular economy application is virtually impossible due to limited information available on costs, sludge properties, and suitability of the recovered materials for specific applications. For example, protein recovered with alkaline pretreatment may not be suitable for applications in the food industry; pathogens and micropollutant contamination should be investigated with respect to possible final uses. In general, physical methods are more easily controllable; however, they may require considerable energy input, e.g., a thermal method will effectively remove odours and pathogens, but usually demand higher energy and capital costs. Chemical methods are effective in the disruption sludge flocs and are easy to operate, but the added chemical costs and possible corrosion issues due to acid or alkaline reagents should be evaluated. Protein loss by mineralization is a possible risk if aggressive oxidants are used. Biological methods, despite their low adverse impacts and effectiveness, are typically limited by slow start-up and process scale-up issues [117]. Since the destruction of microbial cells by any means induces increased dewaterability, sludge processed for protein recovery will result in reduced ultimate disposal needs.

#### 4.1.4. Added-Value Products from Biological Processing of EBSS

In addition to the recoverable biotechnological products just discussed, others such as biopesticides, bioherbicides, and enzymes can be recovered from the EBSS biorefinery. *Bacillus thuringiensis* (BT) is considered the most effective biopesticide in use in agriculture, forestry, and the health sector at present, with specific action against organisms of the orders Lepidoptera (moths), Diptera (flies and mosquitoes), and Coleoptera (beetles). BT forms crystals of proteinaceous δ-endotoxin insecticidal that, due to its target specificity and little or no harmful effects on wildlife, most pollinators, beneficial insects, and humans, is regarded as environmentally friendly. The conventional fermentation medium for BT production involves a significant portion (40–60%) of its total industrial costs; recently, however, waste sewage sludge was found to be a highly nutritional and cost-effective medium for BT [118] and other biopesticides growth, such as endo- and enterotoxins, vegetative insecticidal proteins, hemolysins, enterotoxins, chitinases, proteases, phospholipases, etc. [119]. It has been estimated that the use of EBSS as a growing medium could reduce the industrial cost of BT by about 50% [120].

Enzymes (e.g., lipases, dehydrogenase, glycosidase, peroxidase, and aminopeptidases) are a class of proteins with biological catalyst properties, used in the pharmaceutical, food, and fine chemicals industries to increase chemical reaction rates and, thus, production yield. As such, they contribute to the synthesis of high-value-added products, without undergoing any biochemical transformation. Microorganisms are an important source of enzymes and, due to their fast growth, they produce them more quickly and efficiently than plants or animals; furthermore, since they can secrete abundant extracellular supplies directly into a fermentation broth, they simplify their downstream processing compared to those obtained from higher living organisms.

A large number of nontoxic and nonpathogenic microbes (bacteria, fungi, yeast, and actinomycetes) are known to produce enzymes considered appropriate for industrial applications. Conventional enzyme production occurs on synthetic substrates derived from soybean, fishmeal, glucose, yeast extracts, peptone and other trace elements, which can ultimately account for up to 40% of their industrial production cost. EBSS is an inexpensive and nutrient-rich substrate that could replace conventional substrates, improving the process cost/benefit ratio. Alkaline protease enzyme production via the submerged fermentation or solid-state fermentation of wastewater sludge substrate by *Bacillus licheniformis* was reported [121]. Additional literature confirms EBSS as a substrate from which different enzymes can be obtained, including protease, dehydrogenase, catalase, peroxidase, o-diphenol oxidase, esterase, α-amylase, glycosidases, and α-glucosidase [122,123].

These enzymes have application potential in detergents, leather processing, silver mining, medical, food processing, animal feeds, and various other chemical industries, as well as in waste processing [124]. Sludge-derived enzymes can promote diethylene glycol terephthalate (DTP) and polyethene terephthalate (PET) plastic fibre biodegradation. Naturally produced sludge-derived enzymes have been shown to enhance WWTP operations by improving solids degradation, the hydrolysis of organic matter, and the biodegradation of toxic pollutants [125]. Enzymes are attached to cell surfaces or embedded in EPS or cell structures; their release is improved by disrupting sludge cells [126–128], or by extraction from the solution with cation exchange resins, nonionic detergents, or EDTA [123,129].

#### 4.1.5. Added-Value Products from the Chemical Processing of EBSS

Protein and lipids contained in sewage sludge can also yield bio-oils and chemical added-value products. Thermochemical processes, such as pyrolysis [130–133], gasification [134], hydrothermal carbonization [135], and hydrothermal liquefaction [136] have been tested at the laboratory and pilot scale for the production of bio-oils. Biodiesel, a cleaner mixture of fatty acid methyl esters (FAMEs) compared to bio-oil, can be industrially obtained by methanol transesterification of vegetable oils or animal fats in what is called a “first-generation” biofuel [48]. However, the potential of first-generation biodiesel is hindered by the high cost of the feedstocks, and by the ensuing competition between food and energy, which raises ethical concerns. Nevertheless, biodiesel is among the most promising biofuels that could be recovered from urban waste streams; EBSS, as widely available and nonedible lipid-rich feedstock, could, therefore, represent a viable alternative for its sustainable production. However, bio-oil derived from the sludge protein fraction is high in N and S content, precluding its direct use as fuel; since lipids are considered the major precursor of “good” biodiesel, separation of the protein fraction before pyrolysis can be performed to lower undesired contents in thermally-recovered bio-oil. Biodiesel can then be obtained by the direct esterification/transesterification (i.e., the process of exchanging the organic group of an ester with that of an alcohol) of lipids, with or without the addition of acid or basic catalysts, or enzymes (lipases). Since primary sludge is mainly constituted by soaps and free fatty acids (FFAs) [137], its FAME yield is much higher than from secondary sludge [136], mainly constituted by mono-, di- and triglycerides, phospholipids, and waxes.

Chemical solvent (chloroform, toluene, or methanol/chloroform/water) extraction methods are effective for lipid selective extraction from raw sewage sludge, producing low N and S content feedstocks. Since solvents are relatively volatile, they can be recovered with relative ease after lipid extraction [138]. Liquid–liquid extraction techniques contemplate the use of an organic phase (usually hexane, either pure or with added methanol or acetone) to extract lipids from sludge flocs. Acetone seems to help in the disruption of cell membranes. Liquid/liquid extraction is usually less efficient than with solvent since it is negatively affected by water presence in sludge, which also hinders the subsequent esterification/transesterification reactions. The presence of water residuals is one of the main challenges in the full-scale production of biodiesel from sludge; therefore, dewatering pretreatment is required [139]. Lipids can be extracted from dried sludge, using a hexane/dried sludge ratio of about 10:1, and biodiesel production can then be carried out by acid catalysis [140]. The residual biomass can be returned to the WWTP’s anaerobic digestion reactor for additional biogas production [141].

The limit of organic solvents, such as hexane, is their possible release into the environment during lipid extraction; such release could produce ozone or other photochemical oxidants, or generate process residuals that may contain mineral acids. Furthermore, in the case of residual biomass recirculation to AD, the presence of solvent traces could reduce biogas production capacity by up to tenfold, possibly modifying the process’s economic balance, and worsening its environmental impact [142]. The use of more environmentally-friendly solvents, such as ionic liquids and bio-derived ethyl esters of volatile fatty acids was studied: ethylbutyrate, a green, bio-derived solvent, demonstrated the recovery of more than 90% of saponifiable lipids in primary sewage sludge without the addition of

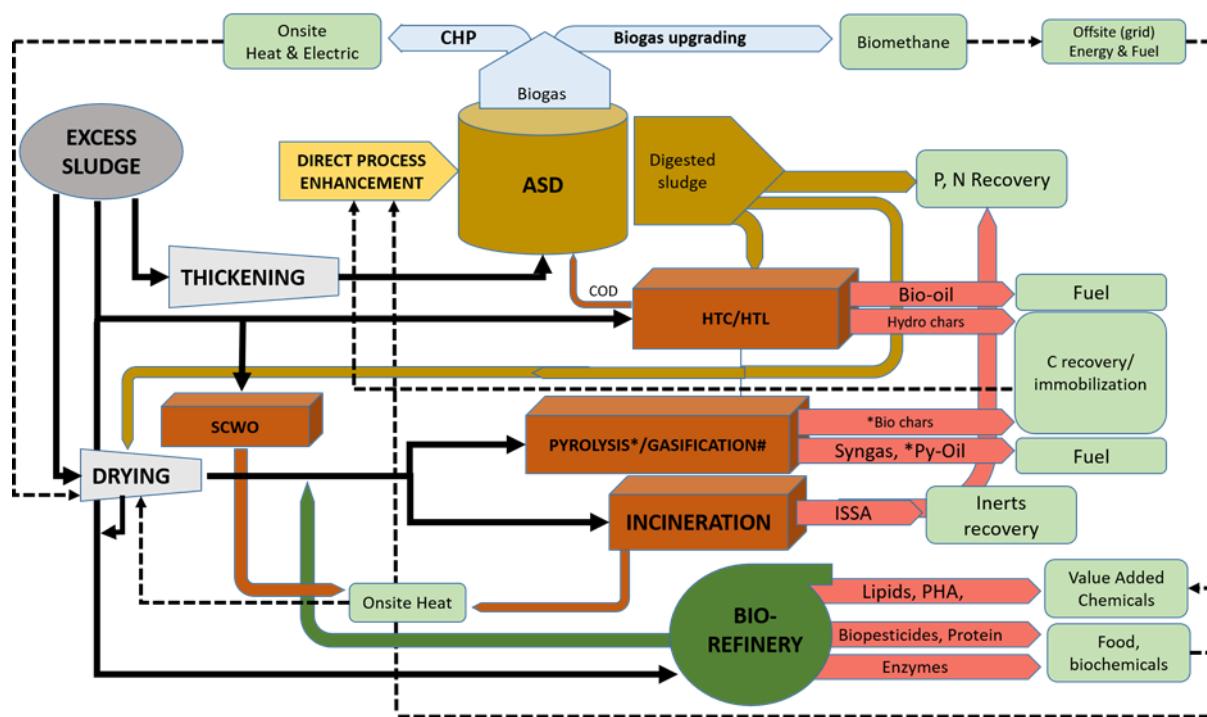
acids, and with greater effectiveness than hexane [137]. Other organic-based, green solvents and ionic liquids (e.g., deep eutectic solvents) or CO<sub>2</sub> (typically used in supercritical conditions) were also indicated as potential substitutes for fossil solvents in lipid extraction. Their excessively high costs and the lack of tested protocols and extracted product certification still constitute significant barriers to the industrial adoption of these substances as fossil solvent substitutes [143]. Other extraction alternatives that have been proposed include sludge sonication and mechanical disintegration, but with yet inconclusive results [144].

Innovative paradigms in wastewater treatment strategies with full implementation of the WRRF concept could favour the use of sewage sludge as feedstock for biodiesel production: new process technologies based on granular sludge can promote the increase in lipid fraction in sludge; in addition, the residual biomass after lipid extraction still contains organic compounds, consisting of about 30% proteins, which can, in turn, be exploited further. Hence, biodiesel recovery by biorefinery can contribute to the improvement of sludge management solutions by embracing both circular economy principles and EU policies concerning sustainable mobility [145].

## 5. Discussion

Sewage sludge biorefinery is an integrated approach consolidating new and established processes to optimize resource recovery and reduce the environmental impact of sludge disposal. Biorefinery does not consist of an exclusive sludge processing method, but it assembles different processes and technologies in order to maximize benefits for the circular economy, and reduce disposal costs and related harmful emissions. As an example, the initially high moisture content in sludge renders it unsuitable for the direct application of thermochemical treatments, such as incineration and pyrolysis, without an energy-demanding, preliminary drying step, which, however, decreases overall thermochemical treatment efficiency and cost/benefit ratios. Since biochemical processing may lead to significant (up to 90%) volume reductions in processed sludge, sludge can then be directed towards the thermochemical pathway with greater efficiency. Biochar generated by EBSS pyrolysis or gasification after lipid/protein extraction can be returned to AD reactors where it can improve process efficiency [146]. Biochar applications in AD showed improved performance in methane, hydrogen, and medium-chain carboxylic acids; the enrichment of functional microbial communities was also observed with enhanced ethanol and butanol production from the microbial fermentation of C1 gases and carbohydrates [147]. In turn, increased biogas production, locally converted to biomethane, can be injected into a centralized gas grid for the centralized synthesis of chemicals, CO, syngas or H<sub>2</sub>, effectively connecting decentralized biomass production sites and avoiding bulk biomass transportation. Figure 4 illustrates possible biorefinery and traditional process interconnections in an integrated sludge management strategy for optimal resource recovery and circular economy exploitation.

Process integration planning needs the quantification of the intervention scale and suitability assessment based on the specific location. Most small WWTPs do not generate sufficient sludge mass to justify and support sophisticated biorefinery processing onsite; however, they may be located close to natural gas lines or industrial districts. In that case, AD could still be an important driver for bio-industry integration, by implementing biomethanation and conveying the gas through natural grids or locally drying sludge and trucking to centralized biorefineries fed by additional substrate streams. The assessment of the expected environmental impacts, economic balance, net carbon footprint reduction and of final products appeal can be reached through life cycle assessment (LCA) and techno-economic analysis (TEA) procedures, to evaluate the impact of products, processes, and services on the environment and the economy [148–154]. These studies, however, have mostly dealt so far with traditional processing scenarios, i.e., incineration, composting, anaerobic digestion, landfilling, and land application [155]; few studies have been conducted on scenarios considering complex biorefinery schemes.



**Figure 4.** Possible process technologies interconnections in an integrated, circular economy-based sludge management strategy.

The viability of sludge biorefinery depends on the efficiency of the system to operate with varying loads and characteristics and must be flexible in design to withstand both short and long-term trends. In this respect, it should be considered that the bulk of municipal organic waste (25–60% of solid waste generated within cities) is food waste, generated in similar or even greater amounts than sewage sludge. Food waste presents characteristics similar to the latter, including high water (typically 80–90% of total weight) and nutrient content; therefore, co-processing of food waste and EBSS could be an ideal strategy for the holistic management of organic urban waste streams. This does not only include anaerobic co-digestion of EBSS and food waste [155–158] but also the advanced biorefinery of combined feedstock [6,159]. Development of biorefinery facilities needs long-term planning: desired/expected products must show the potential of sufficient economic returns and flexibility in response to market demand variations. Savings in sludge disposal costs and the possible elimination of externalities should be factored into the balance to justify the adoption of the necessary investments [160].

To successfully implement a commercial-scale biorefinery, technical, commercial, and sustainability challenges need to be addressed: among these, the optimisation of feedstock logistics is essential, including the improvement of transportation of low-density or wet material with possible decentralized preprocessing [13] and establishing incoming supply chains that could guarantee a steady input of organic feedstocks, for example, by mixing local waste streams with asynchronous seasonal production. Setting up bio-based product distribution networks is also essential for biorefinery sustainability, as the new products must integrate into existing value chains, overcoming difficulties related to the uncertainty associated with novel, unconventional materials that may have limited market appeal. For example, bioethanol can be mixed into conventional fuel up to approximately 15% volume, without the need to modify standard engines; however, not all bio-oils are susceptible to direct fuel use. Lastly, biorefinery development implies relatively large investments; therefore, direct subsidies or tax rebates covering part of the initial costs may be essential for the implementation of these projects. Such subsidies exist in almost all EU countries, although this alone does not constitute a sufficient incentive for engaging in such projects:

well-established regulations and a foreseeable stable income are also necessary to determine the pay-back time of a project, making it attractive [57]. Studies have shown that the sustainability of biorefinery projects is very sensitive to product selling prices, which may be subject to uncertain initial estimates and future market variability, and to investment depreciation schemes. Short-term subsidies and carbon pricing scenarios were shown to be beneficial, but not sufficient alone to make current technologies competitive with traditional fossil fuels in the short term [153].

## 6. Conclusions

Sewage sludge contains high amounts of organics and potentially recoverable materials and should be considered a renewable resource with considerable intrinsic economic potential, whether in the form of energy, nutrients, or materials. The circular economy value of EBSS can be quite high, for example, phosphorus and biochar obtained through thermal treatment can support soil fertilization and amendment; methane from the AD process or bio-oil from the thermochemical process may help achieve greater energy self-sufficiency and reduce GHG emissions; biohydrogen from sludge fermentation can be used as a clean fuel and sludge biorefinery products could substitute raw materials for the chemical and food industries.

Among various technologies for sewage sludge-embedded resource exploitation, the biorefinery is a relatively new and constantly evolving approach capable of integrating different existing processes in an efficient resource recovery chain, while reducing the environmental impacts of sludge disposal. Sludge biorefinery can generate multiple final added-value products, renewable and sustainable, and open unique new perspectives on a less fossil fuel-dependent economy. The potential for industrial applications, however, relies heavily upon issues such as feedstock supply reliability, final product certification and competitiveness, and these issues must still be fully addressed from an industrial perspective. The level of capital investment and operational expenses of biorefinery facilities are strongly dependent upon production scale and applied technologies, but a comprehensive approach and assessment tools for the holistic evaluation of the whole process in terms of environmental, economic, and LCA impacts and benefits are still scarce.

The main challenges for developing technologically mature and economically viable biorefineries based on sewage sludge can be summarized as follows:

- Continuing product innovation: integrated, new urban biorefinery approaches could increase the range of possible final products and their economic and environmental value. Innovative strategies should be investigated for the development of viable sludge biorefineries;
- Marketability within a circular economy approach: biohydrogen production from the AD of carbon-rich sludge is limited by low yield and VFA accumulation, making the process uncompetitive. Protein and enzymes still present higher production costs compared to traditional sources; concerns about animal health still persist in terms of pathogens and metals content; the purification of recovered bioproducts should be further developed to comply with requirements for specific applications to improve their economic added value;
- Process technology: the recovery of metabolic products (e.g., bioplastics, biopesticides, bioflocculants, and biosurfactants) and EBSS postprocessing such as fermentation and enzymatic extraction still require significant TRL optimisation, including scaling-up to pilot or full industrial size; production and extraction of SCVFAs via anaerobic digestion should be further developed;
- Sustainability, social acceptance, and regulatory framework: each scenario needs specific evaluation in terms of yield and composition of feedstocks. The development of assessment tools for processes/product integration and optimization should be promoted. The integration of regulatory instruments, the elimination of legislative barriers, and efforts aimed at improving consumer attitudes could offer important incentives towards the long-term viability of biorefinery schemes.

Sustainable biorefinery design should contemplate the assessment of environmental impact and risk and carbon footprint reduction compared to common sludge disposal practices. Sewage sludge treatment strategies are likely to evolve soon, either towards mono-feedstock “sewage sludge biorefineries” or, possibly “multifeedstock biorefineries” where advanced sewage sludge and other mixed feedstock exploitation processes are carried out. That would depend on local conditions, technology evolution, and the development of an appropriate socioeconomic context. In either case, facilities should be flexibly designed for resilient operation against possible short/long-term variations in sludge and other co-feedstock characteristics and the market demand for final products. The co-processing of sewage sludge, agricultural, and other municipal organic waste streams (i.e., food waste) may improve the long-term economic sustainability of these facilities and could add attractiveness to the adoption of the urban biorefinery.

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