ЕКОНОМІКО-ТЕХНОЛОГІЧНІ ЗАСАДИ БЕЗПЕЧНОГО ВИКОРИСТАННЯ ОСАДУ СТІЧНИХ ВОД В СІЛЬСЬКОМУ ГОСПОДАРСТВІ

Актуальність. Появлення філософії сталого розвитку, згідно якої діяльність зберігає природні та соціальні ресурси для використання майбутніми поколіннями, не завдаючи шкоди економіці бізнесу, а також значне підвищення цен на хімічні добрива через зростання цін на газ вимагають шляхів зменшення хімічного навантаження на сільське господарство. Тенденція відмови від інтенсивних технологій посилюється через економічні вагачі — регламенти Європейського Союзу дедалі частіше забороняють агрохімікати та вводять «податок на вуглець». Тому використання осадів стічних вод як добрив для сільськогосподарського виробництва на засадах економічної ефективності основі стає актуальним питанням.

Мета та завдання. Метою статті є розгляд економіко-технологічних засад, спрямованих на підвищення біодоступності поживних речовин та зниження ризику від використання біовідходів перед надходженням до ґрунту, в контексті реалізації ідеї сталого розвитку.

Результати. Заставосудна осада стічних вод (СВ) у сільському господарстві сприяє впливає на вміст органічної речовини ґрунту, породжуючи проблеми відповідних фізичних властивостей. Всі нерозрізнені характеристики обумовлюють високу цінність даного потенційного ресурсу для господарської діяльності, але потребує використання різних фізико-хімічних, біохімічних та біотехнологічних обробок, щоб усунути ризики шкідливого впливу на ґрунт. Цей процес включає в себе екологічні аспекти, законодавчі вимоги та фактори ризику, які пов'язані з обробкою та підготовкою осаду стічних вод, включаючи переробку за правилами санітарно-епідеміологічної безпеки.

Висновки. Наукові результати та висновки з цього виду досліджень можуть бути використані для розробки економіко-технологічних засад безпечної використання осаду стічних вод у сільському господарстві. Цей процес включає в себе екологічні аспекти, законодавчі вимоги та фактори ризику, які пов'язані з обробкою та підготовкою осаду стічних вод, включаючи переробку за правилами санітарно-епідеміологічної безпеки.

Ключові слова: сталий розвиток, економіко-технологічні засади безпечної використання осаду стічних вод, санітарно-епідеміологічна безпека, дезінфекція осадів стічних вод, економіко-екологічні та законодавчі аспекти, фактори ризику, ризики забруднення ґрунтів, валоризація осаду стічних вод.
ECONOMIC AND TECHNOLOGICAL PRINCIPLES OF SAFE USE OF SEWAGE SLUDGE IN AGRICULTURE

**Topicality.** Spreading the philosophy of sustainable development, where activities preserve natural and social resources for use by future generations without harming the business economy, as well as significant increases in the price of chemical fertilizers due to rising gas prices require ways to reduce the chemical burden on agriculture. The trend of abandoning intensive technologies will be exacerbated by economic leverage - European Union regulations are increasingly banning agrochemicals and introducing a “carbon tax”. Therefore, the use of sewage sludge as fertilizer for agricultural production is becoming an urgent issue. Therefore, the use of sewage sludge as fertilizer for agricultural production on the basis of economic efficiency is becoming an urgent issue.

**Aim and tasks.** The aim of the article is to consider the economic and technological principles aimed at improving the bioavailability of nutrients and reducing the risk of using biowaste before entering the soil, in the context of the idea of sustainable development.

**Research results.** Sewage sludge (SS) application in agriculture has a beneficial effect on soil organic matter content, sorption capacity and an overall improvement in physical properties. Conversion of SS to a soil amendment can be performed by a broad spectrum of methods, which greatly differ by substrate/amendment composition, treatment time, and physicochemical conditions. Sanitary and epidemiological safety is essential, which is why bio-wastes require processing according to selected technologies that aim to improve the bioavailability of nutrients and reduce hazards before entering the soil. This review provides a more complete overview of the present status of the methods for SS disinfection. The review is focused on i) environmental and legislative aspects of SS application in agriculture; ii) risk factors related to the abundance of bacterial, viral, protozoan and other pathogens in SS and methods of SS hygienization by various physical and chemical treatments; iii) risks of soil pollution with biologically active compounds (e.g., antibiotic resistance genes and other emerging contaminants). For the life cycle assessment, an environmental performance and pathogen risk was considered. The results of such consideration have direct impact on the nature of the applied economic and technological measures. Conclusions and perspectives in this field were formulated, using 102 references, including 49 citations dated by the last five years.

**Conclusion.** Numerous technological approaches on SS treatment have their particular advantages, although disinfection efficiency remains unsatisfactory. Legislative requirements are still based on less resistant indicator organisms. Further comprehensive research on SS treatment should be focused on combination of different physical (especially, thermal) and chemical processes, which would convert SS into a qualitative fertilizer with safe microbiological characteristics. The decrease in energy consumption during drying and the reduction of the management costs of these residues can be relevant economic gains. In general, the application of drying to remove water from sewage sludge should be a balance between energy costs in the process and the management costs without drying.

**Keywords:** sustainable development, economic and technological principles of safe use of sewage sludge, sanitary and epidemiological safety, sewage sludge disinfection, economic, environmental and legislative aspects, risk factors, risks of soil pollution, sewage sludge valorization.

**Problem statement and its connection with important scientific and practical tasks.** Sewage sludge (SS) application in agriculture has a beneficial effect on soil organic matter content, sorption capacity and an overall improvement in physical properties. Conversion of SS to a soil amendment can be performed by a broad spectrum of methods, which greatly differ by substrate/amendment composition, treatment time, and physicochemical conditions. Sanitary and epidemiological safety is essential, which is why bio-wastes require processing according to selected technologies that aim to improve the bioavailability of nutrients and reduce hazards before entering the soil.

**Formulation of research objectives (problem statement).** The aim of the article is to consider the economic and technological principles aimed at improving the bioavailability of nutrients and reducing the risk of using biowaste before entering the soil, in the context of the idea of sustainable development.

**Allocation of previously unsolved parts of the general problem.** This review provides a more complete overview of the present status of the methods for SS disinfection. The review is focused on i) environmental and legislative aspects of SS application in agriculture; ii) risk factors related to the abundance of bacterial, viral, protozoan and other pathogens in SS and methods of SS hygienization by various physical and chemical treatments; iii) risks of soil pollution with biologically active compounds (e.g., antibiotic resistance genes and other emerging contaminants). For the life cycle assessment, an environmental performance and pathogen risk was considered. Conclusions and perspectives in this field were formulated, using 102 references, including 49 citations dated by the last five years.

**An outline of the main results and their justification. Environmental and legislative aspects of SS application in agriculture.** *Life cycle assessment.* Sludge production globally in 2017 was 45 MT by dry matter, and now it is increasing annually due to urbanization and population growth (N. Gao et al., 2020)
In this respect, the environmental impact of SS in case of landfill disposal, agricultural use or other applications is of great importance. Particularly, the contribution of different processes of SS treatment for agricultural use is recently studied by (Do Amaral et al., 2021). Energy consumption for SS treatment contributed mostly global warming (>50%), while SS transportation to agricultural areas affected terrestrial and freshwater ecotoxicity, as well as ozone formation – terrestrial ecosystems (Fig.1A, B). Sludge disposal in agricultural areas mostly contributed human toxicity, terrestrial acidification and freshwater ecotoxicity (Fig.1C). The main impacts of SS in soil are related to the presence of Zn, which affects freshwater ecotoxicity and human toxicity (Do Amaral et al., 2021).

Fig.1. Contribution of SS treatment steps in the categories of terrestrial ecotoxicity (A), freshwater ecotoxicity (B) and human toxicity – non cancer (C). By (Do Amaral et al., 2021).

Biogeochemical emissions from SS handling and spreading on land are expected to be minimized in the future by efficient utilization of nutrients and other resources derived from SS, according to the principles of a circular economy (Johansson et al., 2008)(Svanström et al., 2017). The processed land-applied SS can emit volatile chemicals and gases that may act alone or in combination with one another to produce the kinds of symptoms (Schiffman et al. 2000)(Gattie and Lewis, 2004). Groundwater contamination from biosolids with pathogenic microorganisms is one of the greatest problems worldwide, due to the lack of adequate and equitable sanitation of SS (Ranjan et al., 2019). Chemical contaminants in processed SS may potentially interact with microbial pathogens, thus, causing or facilitating the disease process via allergic and nonallergic mechanisms, as well as microbial byproducts (Gattie and Lewis, 2004). Furthermore, endotoxins and exotoxins, which are produced by most bacteria in SS and retain their toxicity at extremely high dilutions, can cause severe illness or death. Endotoxins are heat stable even upon autoclaving, while can be inactivated with dry heat at temperature above 200 °C for one hour (Williams, 2007) (Gattie and Lewis, 2004). A high microbial diversity of SS lead to the horizontal gene transfer and proliferation of antimicrobial resistance (AMR) (Calderón-Franco et al., 2021). The virus persistence in SS is dependent on the physicochemical and biological properties. For example, enveloped viruses survive for 6-7 days in SS (Casanova et al., 2009), while SARS-CoV-2 might persist on the surfaces up to 72h (van Doremalen et al., 2020). Coronavirus can persist in domestic and hospital SS also for a longer period of time at lower temperatures (4 °C) (Wang et al., 2005)(Anand et al., 2022). The factors representing the health hazard upon SS handling and spreading are summarized in Figure 2.

Fig.2. Biogeochemical emissions from SS handling and spreading on land.

Legislative aspects of SS stabilization and guidelines in usage: policy of EU and other countries. The management of SS in EU is regulated by various legislative acts (Table 1). An ex-post evaluation of the SS
Directive 86/278/EEC in 2014 showed that its initial objectives were achieved, in spite of large variations in the amount of SS used in agriculture in the Member States (from none to well over 50%) (European Commission: Ex-post evaluation of certain waste stream Directives, Bio Intelligence Service Final Report, 2014)(Santos et al., 2021).

At present, specific limits for microbiological sludge quality or disinfection treatment requirements are not indicated in the 1986 European Directive on the use of SS in agriculture (European Commission: Council Directive 86/278/EEC 1986) that is still operative. Adopted 30 years ago, the Directive no longer matches current needs and expectations, such as properly regulating pollutants found in sludge (‘emerging contaminants’ like pharmaceuticals and microplastics). Currently (2020-2021), the EU initiated an evaluation of legislation efficiency, as well as the risks and opportunities of SS use in farming www.ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12328-Sewage-sludge-use-in-farming-evaluation_en.

Furthermore, two EU working documents on sludge have been produced since then that considered the sludge hygienization issue: the EU Working Document on sludge (2000) and the EU Working document on sludge and biowaste (2010). The EU Working Document on sludge (2000) indicates that in order to be used without restrictions, sludge should undergo a hygienization process by an “advanced treatment”, which should achieve at least a 6-log-unit reduction of *Escherichia coli* and produce sludge complying with the following limits: no Salmonella in 50 g (wet weight, WW) and *E. coli* <5 00 colony-forming unit (CFU)/g. It is also proposed that sludge produced by “conventional treatments” should show a 2-log-unit reduction of *E. coli*, and its use is allowed with restrictions on its application time, site and modality. Mesophilic anaerobic digestions (MAD) at a temperature of 35 °C with a mean retention time of 15 days and thermophilic anaerobic digestions (TAD) at a temperature of at least 53 °C for 20 h as a batch, without admixture or withdrawal during the treatment, are indicated, among others, as conventional and advanced treatment processes, respectively. The more recent EU document only suggests the limit absence of Salmonella in 25–50 g and *E. coli* < 5×10^5/g WW as possible criteria for the use of sludge in agriculture (Levantesi et al., 2015).

In operational practice, some countries have introduced partial disinfection of wastewater discharged from sewage treatment plants; in Germany – wastewater discharged into recreational areas is disinfected, in France – sewage discharges in protected areas, such as bathing areas and mollusc farming areas, and in Spain – wastewater for agricultural irrigation, fruit trees, sports fields and gardens (HAWRYLIK, 2020).

The most stringent sewage disinfection law applies in the United States (California), where continuous disinfection is carried out (HAWRYLIK, 2020). The US Environmental Protection Agency has worked out in 1993 the Part 503 Sludge Rule for agricultural use, which divides sludge into two categories, Class A (safe

<table>
<thead>
<tr>
<th>Directive</th>
<th>Sector</th>
<th>Targets</th>
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<tbody>
<tr>
<td>1986/278/EEC</td>
<td>Directive on the use of sludge in agriculture</td>
<td>Limits the heavy metal content of sewage sludge used in agriculture</td>
</tr>
<tr>
<td>1991/271/EEC</td>
<td>Directive on urban wastewater treatment</td>
<td>Protection of the environment from adverse effects of urban wastewater, promotion of sewage sludge reuse</td>
</tr>
<tr>
<td>1999/31/EC</td>
<td>Landfill Directive</td>
<td>Reduction of the disposal of biodegradable waste in landfills</td>
</tr>
<tr>
<td>2000/60/EC</td>
<td>Water Framework Directive</td>
<td>Gradual reduction of discharges of pollutants from wastewater into the aquatic environment</td>
</tr>
<tr>
<td>Directive 2000/76/EC</td>
<td>Directive on the incineration of waste</td>
<td>Sets emission limit values for the incineration and co-incineration of waste</td>
</tr>
<tr>
<td>2009/28/EC</td>
<td>Directive on Renewable Energy</td>
<td>Use of sewage sludge to produce energy (i.e. biogas)</td>
</tr>
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</table>

(Izydorczyk et al., 2021).
for direct contact) and Class B (land and crop use restriction supply) (EPA. Technical Support Documents for 40 CFR Part 503. Land Application of Sewage Sludge, 1993). Class A pathogen requirements must be met by one of six alternatives and use of either the fecal coliform (limit of less than 1,000 fecal coliform/g dry weight of solids) or salmonella tests (less than 3 salmonella/4 g dry weight of solids). (EPA, 1993). Other alternatives are shown in Table 2.

### Summary of Part 503 Sludge Rule Pathogen Limits for Class A Sludge

<table>
<thead>
<tr>
<th>All Class A sludges must meet:</th>
<th>Fecal coliform density of &lt;1,000 MPN/gram total solids or Salmonella sp. density of &lt;3 MPN/4 grams total solids</th>
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<tr>
<td></td>
<td>Plus one of 6 alternatives</td>
</tr>
<tr>
<td></td>
<td>1. Time and temperature requirements specified, depending on solids content of sludge.</td>
</tr>
<tr>
<td></td>
<td>2. Alkaline and temperature treatment requirements: pH &gt;12 for at least 72 hours. Temperature &gt;52°C for at least 12 hours, then air dry sludge to ≥50% total solids.</td>
</tr>
<tr>
<td></td>
<td>3. Level of enteric virus and helminth ova prior to pathogen treatment are &lt;1 viable ova/4 grams total solids for helminth ova.</td>
</tr>
<tr>
<td></td>
<td>If levels of enteric virus and/or helminth ova prior to pathogen treatment are ≥1 PFU or if viable ova are present, then test after treatment. Document process operating parameters to achieve &lt;1 PFU/4 grams total solids for virus and &lt;1 viable ova/4 grams total solids for helminth ova.</td>
</tr>
<tr>
<td></td>
<td>4. Levels of enteric virus and helminth ova after treatment and when ready to distribute are &lt;1 PFU/4 grams total solids for virus and &lt;1 viable ova/4 grams total solids for helminth ova.</td>
</tr>
<tr>
<td></td>
<td>5. Use of Process to Further Reduce Pathogens (PFRP). See requirements for composting, heat drying, heat treatment, thermophilic aerobic digestion, beta ray irradiation, gamma ray irradiation, and pasteurization.</td>
</tr>
<tr>
<td></td>
<td>6. Treat equivalent to PFRP requirements. Determined by the permitting authority.</td>
</tr>
</tbody>
</table>


*MPN: Most Probable Number; a all weights are dry weights; b PFU: Plaque Forming Units

According to the EPA Environmental guidelines published in 2000 on stabilization of biosolids products (EPA, 2000), a biosolids product must meet at least one pathogen reduction requirement and at least one vector attraction reduction requirement (derived from (EPA. Technical Support Documents for 40 CFR Part 503. Land Application of Sewage Sludge, 1993). Stabilization Grade A includes thermally treated biosolids (at least 50 °C), high pH-high temperature process and biosolids from unknown processes, while stabilization Grade B – anaerobic digestion, aerobic digestion, air drying, composting, lime stabilization, extended aeration and other processes accepted by the EPA products (EPA, 2000).

Treatment methods should demonstrate the ability to kill even the most resistant organisms, including nonenveloped viruses and bacterial spores (Gattie and Lewis, 2004). However, legislative requirements are still based on less resistant indicator organisms (Gattie and Lewis, 2004).

The development of sewage valorization technologies is limited by legal regulations, in which some European countries do not allow the use of stabilized sewage sludge in agriculture. It is worth mentioning that stabilization is a biological process. On the other hand, the law imposes restrictions on sludge disposal in landfills, which applies to sludge containing > 5% organic matter (Boehler and Siegrist, 2006)(Izydorczyk et al., 2021).

**Indicators of microbiological contamination.** Sewage sludge commonly contains high amounts of human pathogenic bacteria excreted in feces and urine. The abundance of pathogens present in raw sludge indirectly reveals the current health status of the local population (Arthurson, 2008)(Sidhu et al., 2017). Bacteria of the genera: Salmonella (about 1,700 types), Shigella (4 species), Escherichia coli, Vibrio cholerae, Mycobacterium tuberculosis, Pseudomonas aeruginosa, Clostridium perfringens, Bacillus anthracis, Listeria monocytogenes, Streptococcus faecalis, and Proteus vulgaris and viruses of the genera Enterovirus (67 types), Rotavirus, Parovirus, and Adenovirus (31 types) are frequently isolated from SS (Pepper et al., 2006)(Sun et al., 2006)(Paluszak et al., 2012).
These organisms have a strong ability to persistently adapt to changes in the surrounding environment for survival and can be relatively resistant to commonly employed sludge stabilization techniques (Nowicka and MacHnicka, 2015).

In the early 19th century, the total coliforms, fecal coliforms, and fecal streptococci were considered as typical indicator bacteria. Later it was shown that these pathogens are not a major concern in solid waste landfills or leachate (Peterson, 1974)(Anand et al., 2022). Nowadays, different types of bacteria (fecal coliforms and Escherichia coli, Salmonella, Shigella, Vibrio cholerae); diverse parasite cysts and eggs (Balantidium coli, Entamoeba histolytica and Giardia lamblia, helminths); viruses (human adenoviruses, enteroviruses (e.g., polioviruses), diarrhea-causing viruses (e.g., rotavirus), hepatitis-A virus and reoviruses) and fungi are monitored as biological contaminants of SS. All of them can be hazardous to environmental and human health depending on the type and amount (Aghalari et al., 2020)(Anand et al., 2022).

The number of different groups of microorganisms in one g of wet mass of raw SS is shown in Table 3. The disinfection levels required to kill pathogens in SSs are summarized in Table 4.

### Table 3

<table>
<thead>
<tr>
<th>Organism</th>
<th>Type/Genus</th>
<th>Number in 1 g wet mass of sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria</td>
<td><em>Escherichia coli</em></td>
<td>$10^6$</td>
</tr>
<tr>
<td></td>
<td>Salmonella</td>
<td>$10^2-10^3$</td>
</tr>
<tr>
<td>Viruses</td>
<td>Enteroviruses</td>
<td>$10^2-10^3$</td>
</tr>
<tr>
<td>Protozoa</td>
<td>Giardia</td>
<td>$10^2-10^3$</td>
</tr>
<tr>
<td></td>
<td>Ascaris</td>
<td>$10^2-10^3$</td>
</tr>
<tr>
<td>Helminths</td>
<td><em>Toxocara</em></td>
<td>$10-10^3$</td>
</tr>
<tr>
<td></td>
<td><em>Taenia</em></td>
<td>5</td>
</tr>
</tbody>
</table>

(Davis et al., 2013)(HAWRYLIK, 2020).

### Table 4

<table>
<thead>
<tr>
<th>Group</th>
<th>Disinfection level required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial endospores (e.g., <em>Bacillus anthracis</em>)</td>
<td>High</td>
</tr>
<tr>
<td>Nonenveloped viruses (e.g., Norovirus, Coxsackie, Rotavirus)</td>
<td>Intermediate/high</td>
</tr>
<tr>
<td>Helminths (e.g., Ascaris, Toxocara)</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Protozoa (e.g., Cryptosporidium, Giardia)</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Mycobacteria (e.g., <em>M. tuberculosis</em>)</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Fungi (e.g., Candida)</td>
<td>Low/Intermediate</td>
</tr>
<tr>
<td>Vegetative bacteria (e.g., Staphylococcus, Salmonella)</td>
<td>Low</td>
</tr>
<tr>
<td>Enveloped viruses (e.g., hepatitis B, HIV, influenza)</td>
<td>Low</td>
</tr>
</tbody>
</table>

(Gattie and Lewis, 2004).

Data from the Association for the Advancement of Medical Instrumentation (AAMI 1994).

Disinfection levels are based on susceptibilities to liquid chemical germicides; groups increase similarly in resistance to heat, with enveloped viruses being the most sensitive and bacterial endospores the most resistant.

Methods for monitoring of SS microbiological contamination. The testing of SS contamination by pathogens can be performed using a broad spectrum of methods, which represent the both, culture-based approaches and molecular tools. The disinfection effect can be evaluated with a live/dead bacterial staining kit (L7012, InvitrogenTM, Waltham, MA, USA), which is used for staining live or dead microbes in the sludge sample. The differences in fluorescence of live and dead cells are based on the permeability of dyes (e.g., DAPI/PI) through cell membranes (Kim et al., 2019)(Santos et al., 2013).

The presence of *E. coli* can be detected by purple color after cultivation on ChromoCult agar under certain thermal conditions (Levantesi et al., 2015). Salmonella presence/absence is assessed by a five-step procedure comprising: (a) pre-enrichment of sludge in buffered peptone water, (b) enrichment in Rappaport-Vassiliadi medium, selection on two media, namely (c) SMS agar followed by (d) Hektoen enteric agar and, finally, (e) biochemical confirmation of the colonies grown on nutrient agar by MUCAP test (Biolife Italiana, Italy) (Levantesi et al., 2015).

Microbial isolates are cultivated on selective or non-selective nutrient media, afterwards identification is performed using PCR technique, API tests, Phadebact D-Strep Tests and others (Paluszak et al., 2012).
Biochemical testing serves as additional tool for revealing and characterization of target microorganisms. For instance, abundance of fecal coliforms can be measured, using both, plate counts on selective medium and rapid β-D-glucuronidase (GLUase)-based assays (George et al., 2002).

The metagenomic shotgun sequencing on Ion-Torrent platform explores the microbial community structure, their biological interactions and associated functional capacity of SS microbial community (Rimkus et al., 2021)(Sidhu et al., 2017).

Cultivable enteroviruses are eluted from samples according to USEPA standard (USEPA, 2003). Particularly, a liquid raw sludge is conditioned by the addition of 0.0005 M AlCl3. Elution is performed with 10 % beef extract and viruses are concentrated by organic flocculation according to (Katzenelson et al., 1976). Eluted viruses are enumerated by the double-layer plaque assay using buffalo green monkey (BGM) cell line (Levantesi et al., 2015).

**Effect of different SS treatment on the viability of bacterial, viral, protozoan and other pathogens. Physical treatment.** Large quantities of SS are reused in agriculture to recycle nutrients and organic material. Sludge treatment technologies are aimed at preparing a valuable fertilizer, which also meets legislative criteria on sludge hygienization. Numerous technological approaches on SS treatment, which were conducted at ambient temperature or under mesophilic conditions, had a strong effect on biological liquid sludge stabilization and on natural dewatering and drying technologies, although disinfection efficiency was unsatisfactory (Metcalf and Eddy, 2003)(Bauerfeld, 2014) (Junga et al., 2017). In this respect, the present literature review and further comprehensive research on SS treatment should be focused on combination of different physical (especially, thermal) and chemical processes, which would convert SS into a qualitative fertilizer with safe microbiological characteristics.

**Thermal hydrolysis.** Hydrolysis at elevated temperatures shortens the chains of macromolecular organic compounds (for methanogenesis), leads to the dehydration and hygienization of the SS (Xu et al., 2019) (Izydorczyk et al., 2021). Thermal pretreatment includes high (usually between 150 and 250 °C) and low temperature (60–100 °C) thermal hydrolysis, which means increased sludge temperature, usually induced by heat pump (Pilli et al., 2015) (Izydorczyk et al., 2021). The SS treatment at 140–170 °C, 5–35 min contact time and single sudden decompression was reported as optimum (Sapkaite et al., 2017). In another recent study, the temperature regimes of the SS heating zone, the decontamination zone and the cooling zone, as well as the optimum parameters of the sludge layer thickness on the conveyor and the conveyor speed were determined (Dubova et al., 2020). Meanwhile, a continuous anaerobic digestion of SS at 60 °C with a minimum exposure time of 2 h also demonstrated a quite satisfied reduction of Salmonella, E. coli and Enterococcus in the sludge, while the methane production was 10% less, that that conducted at 35 °C and 55 °C (Kjerstadius et al., 2013).

Importantly, that an increased temperature also influences the level of thermally degraded micropollutants, such as drugs, hormones and others (Taboada-Santos et al., 2019)

Thermal hydrolysis has some limitations, specifically, i) the dark color of SS, which can affect UV disinfection; ii) formation of methanogenesis inhibitors, e.g., free ammonia; iii) refractory compounds impact methane production (Ngo et al., 2021). Also energy costs for achieving high temperatures should be considered. Energy and waste disposal costs are offset by savings resulting from no waste landfilling fees (Taboada-Santos et al., 2019) (Izydorczyk et al., 2021).

**Electrical heating.** Electrical heating (ohmic heating (OH)) can serve as a potential method for pathogen inactivation in SS, mostly for onsite sludge disinfection. This method has a long and successful history of application in the food industry for food sterilization (Zhan et al., 2016) and is more recently proposed for disinfection of SS. Sludge temperature reached 95 °C within a few hours at an applied voltage gradient of 600 V/cm (Takhtehfouladi et al., 2015). Formation of chemical byproducts, such as chlorine or H2O2 during electric thermal treatment also can facilitate pathogen removal (Huang et al., 2016).

Recently, Yin et al. (Yin et al., 2018) described this method, using various concentrations of NaCl and NH4Cl as electrolyte to enhance conductivity in sludge mixtures (voltage input 18V with direct current (DC) and alternate current (AC)). Removal of E. coli was greater than 6log10 within 2 h using 0.15M of NaCl as electrolyte. Obviously, this effect was achieved due to electrochemical inactivation in addition to thermal inactivation (Yin et al., 2018). In this process, the solid fraction and conductivity were two critical factors for heat production, which along with energy consumption, is dependent on volume fraction, the concentration of inorganic and organic salts in the sludge mixture and type of current (AC vs. DC) applied (Zhang et al., 2017). DC power offered higher E. coli removal even at lower temperature comparing to AC power. However, it led to severe corrosion on the electrodes, which may hinder long-term application. The
temperature and conductivity were synergistic in ohmic heating process, and heat preservation is the key to promote energy efficiency (Yin et al., 2018).

Another study explains the mechanisms underlying electrochemical (EC) residual disinfection in the presence and absence of primary sludge particulates (PSPs) (Cui et al., 2013). Chloride was detected in PSPs aqueous samples (143mg PSP/L) and its concentration (CC) changed during EC pretreatment: initially, a decrease of CC was observed when EC increased from 0 to 0.28kWh/m3, followed by an increase of CC when EC increased 0.28-0.42kWh/m3. In both cases, k correlated to the initial post-EC chloride concentration (CCI) in an inverse linear relationship. This two-stage change of CC and k was caused by a combination of two reactions: anodic oxidation of chloride and the reaction of chloramines with excess chlorine (Cui et al., 2013).

Solar irradiation. Application of solar energy for thermal disinfection of SS was studied by (Fogolari et al., 2018). The sludge was heated through a heat exchanger built with copper pipes and installed inside the reactor, in which water heated in flat plate solar collectors circulates. In the sets with an average solar irradiation period above 500 Whm−2 the process was effective. Particularly, the reduction of E. coli was between 4.2 and 7.1 units log10; and between 4.8 and 7.4 units log10 of total coliforms (Fogolari et al., 2018). Among the limitations of this approach, weather conditions are likely to be the most important, i.e., decreased temperatures due to lower levels of solar irradiation (Fogolari et al., 2018).

Another approach of using the solar energy for SS disinfection has been suggested by (Paluszak et al., 2012). The solar drying process of SS was performed on technical scale in Poland with the aim to estimate the sanitization effectiveness. The survival of Escherichia coli, Salmonella Senftenberg W775, enterococci and Ascaris suum eggs served as estimation criteria. The long-term solar drying (up to 168 days) did not result in sufficient reduction of microbial count. The results of this study indicated that solar drying does not guarantee biosafety of product (Paluszak et al., 2012).

Drying/biodrying of sewage sludge in reactors. Thermal drying results in volume reduction and microbiological inactivation, hence its use can be considered a powerful tool in the environmental area.

Drying of SS or digestate in the vacuum chamber was tested in a batch-processing pilot device. This process consumes approx. 1 kWh/dm3 of evaporated water and, therefore, reaches a price of 180–240 Euros/t dry matter. Meanwhile, heavy metals were adsorbed on magnetite nanostructures, that decreased the level of heavy metals in the SS up to 20% in one cycle (Bratina et al., 2016). This drying technology is economically sustainable due to the low vacuum and temperature (35 °C–40 °C), that increases the efficiency of the heat pump (coefficient of performance 5–7.2) of the energy produced by the anaerobic digestion (Bratina et al., 2016).

Another effective technique for the pretreatment of SS for agricultural purposes is the bio-drying, which uses the heat generated by the aerobic activity of microorganisms, aided by the airflow (Pilnáček et al., 2019). Regarding disinfection efficiency, E. coli were completely eliminated, while the enterococci content was reduced by 4 orders of magnitude (Pilnáček et al., 2019).

The drying process conducted with an upflow direct convection dryer was assessed for bacteriological disinfection (Serenotti et al., 2010). Authors reported that the most favorable drying condition was at 140°C and flow of 0.4 kg/min. Disinfection efficiency was satisfactory (E. coli and Salmonella spp.), since the sludge was exposed to > 60°C for more than one hour (Serenotti et al., 2010).

Pasteurisation. Pasteurisation is a process of thermal decontamination of SS (digestate, less often raw) at 65 °C - 90 °C, for 5 to 30 minutes. Classical pasteurization results in destroying the vegetative forms of microorganisms, helminths eggs and viral pathogens, while microbial spores die only at temperatures above 100°C. At least two separate rounds of pasteurization are needed to eliminate endospores, that is expensive (HAWRYLIK, 2020)(Rabbani and Hooshyar, 2011). Pasteurization at 70 °C for 30 min destroys more than 99% of Taenia saginata ova, Salmonella and Enteroviruses were completely inactivated. Heating sludge at a lower temperature for a longer period of time (55°C for 2 h) resulted in a similar outcome (Bitton, 2005)(Rabbani and Hooshyar, 2011).

Junga et al. (Junga et al., 2017) compared the efficiency of SS disinfection by autothermic aerobic thermophilic stabilisation (AATS) by pure oxygen and the method of sludge hygienisation by pasteurization. Both hygienisation technologies meet legislation requirements for application to agricultural soil (Junga et al., 2017).

Microwave irradiation. Another SS thermal method, i.e., microwave radiation, is referred to as an environmentally friendly technique, mainly due to its reduced emissivity (Izydorczyk et al., 2021). Along with decomposition of flocs, microwaves facilitate SS hygienization (Grübel et al., 2019). Microwaves are often used as a supporting method, e.g., in acid or alkaline hydrolysis. However, the yield increase in
alkaline hydrolysis was 30% higher than in acid hydrolysis. This leads to a higher yield of biogas (Beszédés et al., 2009). Treatment of SS with microwaves in the presence of NaOH is applied for obtaining struvite crystals, which precipitate after decomposition of organic compounds containing phosphorus and transforming it into an inorganic form (Wang et al., 2017)(Izydorczyk et al., 2021).

The microwave enhanced advanced oxidation process (MW/H2O2-AOP) is designed for the pasteurization and stabilization of SS to meet and maintain Class A biosolids criteria. Reduction of fecal coliform concentrations were below detection limit (1000CFU/L) immediately after treatment when sludge was treated at 70°C with more than 0.04% of H2O2 (w/w). The soluble chemical oxygen demand increased with an increase of hydrogen peroxide dosage at 70°C (Yu et al., 2010).

Sonication. Ultrasound (US), i.e. vibrations with a frequency of 20–100 kHz, are sound vibrations that interrupt the continuity of cellular shields. The effectiveness of US disinfection depends on the intensity, frequency, duration of ultrasound and the type and number of microorganisms destroyed. The use of low and high frequency US in disinfection of SS on an increasing scale have been recently discussed (HAWRYLIK, 2020).

Sonication disintegrates sludge and the microorganisms in it. This has a hygienic significance, which furtherly allows for wider use of sludge. Tian et al. (Tian et al., 2015) described the pretreatment of sewage sludge with ultrasound-assisted alkali hydrolysis by means of which they achieved a significant increase in COD (from 1200 to 11,000 mg/L). Besides, the use of sonification favoured the biodegradation of sludge, leads to an increase of humic substances (Farooq et al., 2009). The use of ultrasounds to support hydrolysis ensures greater amino acid extraction (J. Gao et al., 2020). The higher the water content in SS, the more efficient sonication is (Zhang et al., 2007)(Izydorczyk et al., 2021).

Freezing and dry ice. Dry ice is a carbon dioxide in the solid state which is formed by expansion of liquid carbon dioxide under normal conditions (temperature of 273 K (~0.15°C), pressure of 1013.25 hPa). The dry ice sublimes at –78.5°C and a pressure of 1013.25 hPa. Its heat of sublimation is 573 kJ, which means that it is approximately 3.3 times more effective coolant than water ice (with the same volume). Its specific gravity comprises in the range from 1.2 to 1.6 kg/dm3, and its hardness on the Mohs scale is 2, which corresponds to the hardness of gypsum. It is anhydrous, non-flammable, non-toxic and has no smell or taste (Nowicka and MacHnicka, 2015). The total number of bacteria in 1 g of the volume ratio of the SS to dry ice 1 : 1 was reduced by 76%, the number of Salmonella sp. rods decreased by 90%, while the number of Clostridium perfringens rods decreased by 85%. The disintegration of the sludge by dry ice resulted in the release of organic matter into the liquid phase and the increase in turbidity of supernatant liquor. CODCr value increased by 549 mg O2 dm–3, and the turbidity of liquid by 320 mg SiO2 dm–3 (Nowicka and MacHnicka, 2015).

The effect of the rapid freezing method, using the endothermic reaction of the CO2 gas hydrate dissociation, applied to sludge cell lysis on the viability of microorganisms in sludge was investigated by (Kim et al., 2019). A gas Hydrate dissociation-energy-based Quick-Freezing treatment (HbQF) was applied for SS cell rupture and dewatering. Carbon dioxide and water molecules in sewage create CO2 gas hydrates, and subsequently the sludge rapidly freezes by releasing the applied pressure. HbQF releases organic materials from sludge floc and microbial cells; reduces cell viability by cell lysis; followed by gravitational settling could be the solution to dewater sludge (Kim et al., 2019).

Gamma irradiation. Gamma irradiation-disinfection of SS was shown as a reliable, fast and efficient method for safe sludge recycling (Wang and Wang, 2007). A total radiation dose of 1 kGy effectively reduced the development of potentially infective larvae in a sludge containing 20% solids, by 99%. Higher doses of radiation up to 10 kGy did not achieve a 100% kill. Complete inactivation could be obtained when 0.5 kGy radiation was applied at 50°C to a sludge containing 3% solids and when 0.4 kGy radiation was applied at 55°C to a sludge with 20% solids (Melmed and Comninos, 1979). The influence of 10 MeV electron beam on bacteria, parasites and parasite eggs present in SS from different municipal sewage treatment plants in Poland was studied in 1995 by (Chmielewski et al., 1995). More recent studies confirmed the SS disinfection efficiency by gamma irradiation. Among indicator organisms, Streptococcus faecalis were the most resistant towards gamma irradiation and were eliminated at 3.5 kGy, while E. coli — the most sensitive with lethal dose at 2 kGy. No Ascaris larvae were viable after exposure to 1.0 Kgy following incubation of exposed ova for four weeks period (Author)(Musaad, 2008). The results of field trials with gamma-irradiated SS and onion (Allium cepa) proved that the gamma irradiated sludge material was of equal quality compared to the conventional farmyard manure (Rathod et al., 2009).

Raw and pasteurized SS was treated at different dose treatment of 1.5, 3 and 5 kilogray (kGy) gamma irradiation individually and for 3 kGy sufficiency was achieved. Decrease in irradiation dose from 5 to 3 kGy...
was observed for pasteurised sludge resulting in saving of radiation energy. The presence of heavy metals in untreated sewage sludge has raised concerns, which decreases after irradiation (Priyadarshini et al., 2014).

Greenhouse experiments with gamma-irradiated SS and Ocimum basilicum L. showed that application of ≤ 30 g SS irradiated with 5 kGy absorbed dose of gamma-ray per kilogram soil can be suggested under similar conditions (Asgari Lajayer et al., 2019).

**UV radiation.** The basic mechanism of bactericidal action of UV rays is associated mainly with changes induced in nucleic acids, mainly in DNA nucleotides. However, the presence of solid particles and suspended solids in the wastewater reduces the effectiveness of the UV disinfection process (HAWRYLIK, 2020). There are three principal factors involved in this interference: (a) the number and size of particles, which could cause dispersion of radiation and occurrence of shading areas; (b) the nature of particles (organic or inorganic); and (c) the degree of association of microorganisms and particles, which protects the microorganisms from UV radiation (Bennamoun et al., 2013).

The least resistant to UV radiation are bacteria and viruses, slightly more yeast, and most moulds. Spore forms are more resistant than vegetative forms. UV-C radiation with a wavelength of approx. 254 nm shows the highest disinfecting efficiency against microorganisms. The UV treatment of an activated sludge resulted in average human noroviruses NoV and *E. coli* reductions of 2.9log10 and 5.2log10, respectively (Campos et al., 2013). Another study showed that UV disinfection was not completely efficient regarding the inactivation of Giardia cysts in wastewaters (Neto et al., 2006). Several studies on the inactivation of protozoa by UV radiation have shown inactivation at a UV dose of 20 mJ cm⁻² (Santos et al., 2013).

**Vortexing.** The mechanical treatment of the SS in the vortex layer apparatus (VLA) using the energy of the rotating electromagnetic fields of high intensity, was studied by (Litti et al., 2019). The treatment in VLA during two minutes resulted in the total destruction of the protozoa bigger than 20 μm. Technological modes used enabled the effective destruction of the structure of activated sludge flocs. However, the death of the free-flowing and aggregated microorganisms of SS was insignificant. This suggests the need for the selection of more efficient processing mode by changing frequency of the magnetic field, the ratio of the working bodies to the chamber volume and geometrical parameters of the working bodies in VLA (Litti et al., 2019).

**Chemical treatment. Chlorination.** The use of chlorine is the cheapest and the most common disinfection method. The effect mainly depends on the composition of sewage, chlorine dose, pH, temperature, contact time, type and number of microorganisms. As the reaction progresses, the pH increases, the sewage temperature decreases, the dose and contact time decrease, the disinfection effects decrease (Dietrich et al., 2007). At pH values below 5.0, chlorine compounds remain in the dissociated form, and they dissociate when the pH increases significantly. The ions formed are a much weaker disinfectant than undisassociated forms. For disinfection of sewage and SS, the most commonly used are: chlorinated lime, calcium hypochlorite (Ca(ClO)₂ x 4H₂O), sodium hypochlorite (NaClO x 5H₂O), chlorine (as chlorinated water) and chlorine dioxide. All forms of chlorine are very corrosive and toxic and, if not handled properly, can be very dangerous. Typical concentrations of chlorine gas used to disinfect the outflow from a municipal sewage treatment plant range from 5 to 20 mg/dm3 at 30–60 min. contact time (the condition is low suspension content). Chlorinated lime and calcium hypochlorite are usually used in small sewage treatment plants and for disinfection of screenings, sand from sludge, in particular raw sludge. The most effective chlorine inactivates bacteria. Viruses, bacterial spores, cysts and protozoa oocysts (*Cryptosporidium parvum, Giardia lamblia, Entameba histolytica*) and helmint eggs are more resistant to chlorine than bacteria. Due to the formation of organochlorine compounds, continuous disinfection of municipal wastewater with chlorine compounds should not be used (Dietrich et al., 2007)(HAWRYLIK, 2020). Humic substances mainly humic acids constitute the major fraction of natural organic matter in water supplies. They play an important role in the formation of harmful disinfection by products (Mahvi et al., 2009). Disinfection byproducts include trihalometans (THMs), haloacetic acids and halocetonitriles that are mutagens/carcinogens and tratogens (Rabbani and Hooshyar, 2011).

**Ozonation.** Ozone treatment is a unique method of disintegration of sewage sludge, due to the lack of formation of by-products. Ozone with 2.07 V oxidizing potential (at pH 7) is one of the strongest oxidants used in wastewater treatment. Ozone destroys bacteria much more effectively than chlorine. It is an effective microicide that destroys all microorganisms potentially found in wastewater, including viruses as well as protozoan cysts and oocysts. The process of microorganisms inactivation occurs rapidly even at low ozone concentrations (e.g. 13 mg/dm³), at residual concentrations (1 mg/dm³) of chlorination-resistant microorganisms, e.g. protozoan cysts *Cryptosporidium* and *Giardia* (Janex et al., 2000). The effectiveness of the ozonation process depends on the susceptibility of organisms, contact time and ozone concentration.
(Nasuhoglu et al., 2018). The ozonation process is short (10–30 minutes), and ozone doses for biologically treated sewage are in the range from 15 to 30 mg/dm³. Although ozonation is a recommended method for technological reasons, it is associated with high economic costs, which limits its use (HAWRYLIK, 2020).

Currently, there are also attempts to use alternative methods that are a combination of physical and chemical processes, or using advanced oxidation methods with high efficiency in neutralizing pathogens, such as PEROXONE (dosing into ozone-treated hydrogen peroxide) (Gassie and Englehardt, 2017)(HAWRYLIK, 2020).

Acidic hydrolysis. Performic acid (PFA) is the strongest oxidant used for disinfection with an oxidizing potential of 2.70 V. Its effectiveness has been confirmed in the inactivation of pathogenic microorganisms, including viruses and bacterial spores. The highest PFA activity is shown at the pH close to 7.0 (at higher pH values, the PFA activity decreases), also a decrease in temperature decreases its activity (Lenntech, 2014). PFA does not generate by-products and does not increase the biological or chemical oxygen demand, disinfects quickly and then decomposes into carbon dioxide and water (Porat et al., 2019). Despite the low durability of performic acid, PFA is used in wastewater disinfection. Disinfection of outflows after the first treatment stage with PFA at a dose of 6 mg/dm³ at 45 min. contact causes complete removal of faecal coliforms (Porat et al., 2019)(Tondera et al., 2016)(HAWRYLIK, 2020).

Peracetic acid (PAA) is considered an effective disinfectant to fight bacteria, viruses, fungi and spores, which has a stronger oxidizing potential than chlorine and chlorine dioxide. Apart from high efficiency of bacterial and virus neutralization as well as low level of by-product formation, the advantages of PAA include the lack of influence of the pH value on the process efficiency and short contact time required. The use of PAA at a concentration not exceeding 1 mg/dm³ does not contribute to the formation of mutagenic products in wastewater. The product of PAA decomposition is acetic acid, which is an easily biodegradable compound. This feature causes danger of secondary microbial growth in wastewater without residual peracetic acid. PAA can be used to disinfect all types of wastewater, also in the presence of organic matter, but the disinfection efficiency is clearly weaker in the case of outflows after the first treatment stage (Zhang et al., 2019). A serious limitation of the use of PAA in wastewater disinfection is its high cost. The use of PAA in the hygienization of SS reduces the viable fraction of all bacteria within 12 hours after application, including vegetative forms capable of forming spores (Arthurs, 2008)(HAWRYLIK, 2020).

The performance during field trials of a proprietary peracetic acid compound (containing 36 to 40% w/w peracetic acid), hereafter referred to as PAA (100%), is described. These trials under operational conditions showed it to be a suitable bacterial and ovicidal agent for the disinfection of raw, digested and activated sludges. Concentrations ranging from 250 to 1000 mg PPA/1 have achieved up to 99% inhibition of hatching and up to 100% destruction in viability of tapeworm embryos suspended in raw and digested sludges. Similarly these concentrations resulted in 5 log reductions in salmonellae seeded in raw sludge. A dose of 250 mg PAA/1 reduced salmonellae levels from 4600 organism/100cm³ to < 30/100cm³ during gravity thickening of surplus activated sludge. Results from 46 tanker loads of consolidated surplus activated sludge revealed that salmonellae levels were reduced from 2400 organisms/100 cm³ to < 30/100 cm³ at doses of 500, 400 and 300 mg PAA/1. At a lower dose of 150 mg PAA/1 levels were reduced to within a range of < 30 to 430 organisms/100 cm³. At optimum disinfection concentrations for the destruction of both bacteria and parasites, PAA was rapidly utilised resulting in safe, readily biodegradable, non-toxic residuals. The technical and practical benefits, principals of disinfecting sludge and ecological safeguards are highlighted in this paper. Use is made of case histories to describe practical operating techniques (Bauerfeld, 2014).

Alkaline hydrolysis. Addition of an alkaline stabilizer (e.g., lime) increases the temperature and pH of sludge, which leads to the elimination of pathogenic organisms and reduces the problem of odour (Wong and Fang, 2000). Santos et al. (Santos et al., 2020) conducted sanitary tests after chemical treatment to determine the presence of microorganisms in sewage sludge from 12 municipal sewage treatment plants. Alkaline industrial waste (limestone mud, volatile coal ash, eggshells) and calcium hydroxide were used as chemical conditioning agents. Each of these materials was mixed with the precipitate and contacted for 24 h. Among the materials tested, only eggshells (a source of CaO obtained during calcination) and calcium hydroxide eliminated E. coli (for any dose tested: 0.05–0.15g/g SS). In case of CaO, an increase of pH induces permanent changes in ionization of the structural components of cellular proteins of microorganisms (especially in the case of anionic and carboxylic groups). This leads to irreversible modifications of their structures and disrupts the activity of the enzymes (Santos et al., 2020). As was recently reported by (Wolny- Koladka et al., 2020), addition of 5% of CaO has showed the strongest antimicrobial properties, and it can be recommended for hygienization of the analyzed materials and for the reduction of the risk of self-heating.
during their storage in windrows (after the mixing process there was no secondary temperature increase) (Wolny-Koładka et al., 2020). Experiments with raw sludge amended with calcium oxide and activated zeolite in the amount of 2.5-5.0 % and 20-30 % by weight, respectively, stop the fermentation processes, provides disinfection, dehydration and structuring of SS, promotes the immobilization of heavy metals (Shagidullin et al., 2021).

Sludge, whose stabilization and hygienization is done with alkaline material, have high pH and lower amount of nitrogen, due to volatilization losses of ammonia. Sludge in liquid form has more K, because it does not suffer dewatering in its production (Bittencourt et al., 2016).

Experimental alkaline treatment to eliminate pathogens (bacteria and worm eggs) was also carried out by (Lopes et al., 2020). Sewage sludge was mixed with hydrated lime. It was noted that some bacteria (Geobacter and Geothrix) were still present in the lime-treated SS despite strongly alkaline conditions (pH >12) (Lopes et al., 2020)(Izydorczyk et al., 2021). The results reported by (Farzadkia and Bazrafshan, 2014), showed that SS stabilization with hydrated lime reduced fecal coliforms more than 99.99% and also stabilized sludge covered standards of class B of USEPA criteria. Another study showed that bentonite addition of lower than 5% was acceptable for the sludge compost amendment, which had great potential in sludge hygienization, detoxification and heavy metal passivation (Zhou et al., 2017).

Drying adjuvants, composting. Energy consumption is the most significant disadvantage of thermal drying. Thus, it is essential to find a strategy to reduce energy requirements. In this context, industrial wastes (e.g., coal fly ash and green liquor dregs) have been used as drying adjuvants (Gomes et al., 2020).

The process efficiency is not only dependent on drying equipment and chemical conditioning but also the bound water content and its distribution in the sludge. Four different physical states of water constitute the sludge: (i) free water, which is not related to solid particles; (ii) interstitial water that is trapped inside interstitial spaces of the sludge flocs and microorganisms; (iii) surface water, which is retained in the surface of the material through adsorption and adhesion; and (iv) internal water that is chemically linked in the sludge. The sum of interstitial, surface, and internal waters can be classified as bound water (Bennamoun et al., 2013)(Santos et al., 2021). Thus, the redistribution of water may have affected the drying time. Another factor to consider is the morphology of the mixtures (SS with adjuvants). The adjuvants studied showed a reduction of about 10% in shrinkage compared to raw SS. Overall, the drying adjuvants can act as skeleton builders and create channels to vapor release, contributing to the improvement of the process. (Santos et al., 2021).

Lime mud (LM) from pulp and paper mills is an inorganic by-product generated during the causticizing reaction in kraft processes for recovery chemicals in the pulp mills. This by-product is mainly composed of CaCO₃, and thus it can be valorized as neutralizing agent or in liming applications. According to industrial information, about 25 kg of LM per ton of pulp air-dried are commonly produced and currently, landfill disposal is the main management route. However, LM may not only assist the water diffusion from SS in the thermal drying process but also the final product can own liming capacity for soil applications. Thus, this study aims to valorize LM as a SS drying adjuvant to produce an organic-rich product, containing macronutrients and without pathogen contamination for agricultural applications (Santos et al., 2021).

Santos et al. (Santos et al., 2021) compared the performance of six residues not only as drying adjuvants of SS but also as improvers agents in agronomic properties of the final product. According to criteria in line with circular economy and industrial ecology, the selected adjuvants were weathered coal fly ash (CFA), bottom biomass ash (BBA), green liquor dregs (GLD), lime mud (LM), eggshell (ES), and rice husk (RH). The main physicochemical properties of these materials were determined. Then, small cylinders with and without 0.15 g adjuvant/g SS wet basis were shaped at room temperature and dried at 130 °C in a moisture analyzer to evaluate the drying kinetics. The profiles were modeled, and the main parameters determined. Furthermore, several relevant parameters for agronomic applications of the final products were determined, such as pathogen contamination, acid neutralization capacity (ANC), and oxygen uptake rate (OUR). Adding BBA to SS (named as SS_BBA product) promoted the highest diffusion coefficient (2.55 × 10−7 m²/s) and drying rate (41.6 g H₂O/kg.min). On the other hand, SS_ES showed a positive impact in almost all agronomic parameters, with an ANC of 0.166 g CaCO₃/g, OUR of 10.18 mmol O₂/kg organic matter h, and germination index of 29.1%. In general, the results indicate that several residues can be used to improve not only sludge drying but also the final properties of the product for soil applications (Santos et al., 2021).

Co-composting conditions of mixtures (maximum 50 °C for at least 5 months in semi-arid climate) containing half and one-third of the sludge were adequate for a rapid destruction of pathogens, compared to mixture containing two-third of the sludge (El Hayany et al., 2021).
Conclusions and perspectives. The disinfection degree, which is influenced by a variety of interacting operational variables and conditions, is however, highly dependent on time and temperature (Junga et al., 2017). The dry mass content constitutes a very important technological parameter of the sludge (Bartkowska and Wawrentowicz, 2018). The disinfection approaches should be optimized in order to minimize potential adverse impacts like antimicrobial resistance (Anand et al., 2022). Although the disinfection methods such as chlorination, radiation or ozonation that are commonly applied to wastewater effluent, nevertheless, they are not suitable for sludge treatment. Development of effective technology for onsite sludge disinfection is necessary and urgent (Yin et al., 2018). Several studies have experimented with hybrid methods where two or more technologies can be integrated to increase treatment efficiency and performance (Anand et al., 2022).

Unfortunately, pathogen regrowth is an inherent problem with all sludges rich in proteins, amino acids, and other forms of organic nitrogen and sulfur—regardless of how they are processed. Once the materials are applied and become wet, they are colonized by bacteria and fungi; the materials then decompose and emit noxious odors in the form of organic amines, organic sulfides, and other small-molecular-weight compounds. Offensive odors that form as sludge biologically decomposes in the field indicate pathogen regrowth because they are produced as bacteria break down proteins and other organic compounds containing nitrogen and sulfur (Gattie and Lewis, 2004).

Economic aspects of SS hygienization have been analyzed by (Diocaretz and Vidal, 2010). Authors quantified the mass and energy balances for a supply of 100 t of sludge, using different disinfection approaches. Thus, the solar dehydration and chemical treatment with alkali consume 11.7 and 148.3 kW/h with production of 80t and 99.6t, respectively. In turn, the most expensive technology is gamma irradiation, which consumes 64800 kW/h for obtaining 97.6 t of the product. The thermal drying also requires quite a high energy consumption, i.e., 21000 kW/h for 20t product. The composting does not consume electricity (Diocaretz and Vidal, 2010). The high costs of thermal hydrolysis and ultrasonic methods and the need for a neutralizing agent in acid solubilization limit the rapid implementation of these processes in industrial practice (Izydorczyk et al., 2021).

The key in future implementation of SS valorization technologies is to identify process parameters and their impact on the rate of protein extraction, energy consumption, material consumption and cost, quality of protein hydrolysate and efficiency of sludge dewatering (Izydorczyk et al., 2021) (Fig.3).

Comparing the costs of different sludge disposal methods, the application on land and agriculture involves the lowest cost compared to composting, drying, incineration, and landfill. Some studies indicate that SS is an efficient replacement for chemical fertilizers, especially phosphorus. Indeed, Switzerland, Germany, and Austria are developing legislation to make P recovery mandatory from municipal sewage sludge (Challenge, 2014)(Santos et al., 2021). The decrease in energy consumption during drying and the
reduction of the management costs of these residues can be relevant economic gains. In general, the application of drying to remove water from SS should be a balance between energy costs in the process and the management costs without drying (Santos et al., 2021).

**Conclusions and perspectives of further research.** The operation of devices, machines or installations is still underestimated in society. Perhaps, this is due to the fact, that the concept of operation is an interdisciplinary issue. It includes the organizational, technical, ecological, economic and social issues related to the activity and operation of people and machines. In engineering terms, it can be defined as a set of activities including planning, using, servicing, diagnosing, storing and others, aiming at the safe use of installation/devices and extending the period of its/their operation. The analysis of technical and technological parameters of the implemented process can also serve this purpose (Bartkowska and Wawrentowicz, 2018).

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