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State-of-the-art Overview of Biological Treatment of Polluted Water from Rice Mills and Imminent Technologies with Green Energy Retrieval

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ABSTRACT

Rice milling involves shelling and polishing paddy grains to produce rice- both raw and parboiled. Parboiled rice production requires a massive quantity of freshwater for soaking, which, in turn, generates a large amount of wastewater. If this wastewater is not properly ameliorated, it can cause tremendous troubles of surface water pollution, land pollution, and, ultimately, groundwater pollution. Therefore, proper treatment of polluted water from rice mills (PWRM) as per the effluent discharge norms is necessary to protect the surface and subsurface water resources for sustainable development. There are two methods for remediating rice mill wastewater- physicochemical and biological. The biological methods produce comparatively less sludge and are cost-effective. Moreover, these processes are capable of retrieving green energy in the form of biomethane, biohydrogen, and bioelectricity to augment bio-fuel production, aiming to meet the ever-increasing fuel demands caused by rapid industrialization, motorization, and urbanization. The focus on green energy production is gaining momentum day by day due to the adverse effects of conventional energy derived from fossil fuel combustion in terms of enhanced Air Pollution Index (API) in the ambient atmosphere. In this paper, anaerobic biodegradation, phytoremediation, phyco-remediation, and microbial fuel cell techniques adopted by various researchers for remediating the polluted water from rice mills have been well addressed and critically discussed. The pros and cons of these biological methods have been well addressed to assess the socio-techno-economic feasibility of each method.

INTRODUCTION

Rice is the prime food-grain crop of India. India is the next biggest paddy grower on the planet, with an annual production of 118.9 million tons (MT), followed by China with an annual production of 146.7 MT (Statistica 2021). Rice is produced from paddy, usually in a rice mill. As per the consumer market's demand, stakeholders in the agro-industrial sector produce two types of rice: parboiled rice and raw rice. The parboiled rice is produced by soaking and steaming the paddy in the parboiling unit, drying the paddy to a moisture content of 14%, and ultimately milling the dried paddy to produce parboiled rice. The raw rice is directly produced from paddy by milling after cleaning and drying to the moisture content of 14% (Araullo et al. 1976).

The production of edible rice is a fast-growing industry that has a pivotal role in the country's economic growth. There are about 1,30,000 rice mills in India (FNB News 2022) and more than 1,500 rice mills in Chhattisgarh, including modern rice mills (Department of Commerce & Industries Chhattisgarh 2022). The parboiled rice mills generate a huge amount of wastewater in the soaking operation of the paddy. Industrial wastewater has a deleterious effect on biological diversity, mainly due to its pollution potential . Due to this, wastewater can have severe adverse effects when discharged into natural water bodies without proper treatment (Galvez et al. 2003, Alderson et al. 2005).

Rice constitutes a vital component of the dietary regime for nearly 50% of the world's demography. It provides nearly 21% of the world's food intake and 15% of each protein. Three basic steps to prepare partially boiled rice are soaking, boiling, and drying the paddy before milling. Preference for parboiled rice includes traditional flavor, non-sticky grain structure, and enriched nutrients (Kato et al. 1983, Unnikrishnan & Bhattacharya 1987, Heinemann et al. 2005). However, the paddy from the crop area flooded during harvesting results in breakdown during shelling and polishing operations (Bhattacharya 2011). To tide over this problem, partial boiling of paddy is done to reduce breakage and optimize the production of whole rice grains during these operations.

The quantity of water used for soaking paddy during parboiling is approximately 1.25 times the quantity of paddy to be soaked. The liquid rice mill effluent is produced at nearly 1.0-1.2 liters per kilogram of milled paddy (Rajesh et al. 1999). Continued disposal of this polluted water causes the degradation of water bodies, where algal blooms and eutrophication thrive. Thick layers of algal blooms block sun rays from entering the water in depth, resulting in the drooping of these plants. The drooped plants are degraded by bacteria that utilize large amounts of dissolved oxygen (DO) from the polluted water. As a result, the polluted water is rendered to an oxygen starvation condition for a while. This oxygen starvation condition promotes the microbial species that release toxins. The oxygen starvation state and accumulation of toxic residues in the water eventually result in the death of water creatures like fish and zooplankton (Karul et al. 2000).

The rice mill industry produces several forms of pollution that transit from air to water, soil, and, ultimately, groundwater pollution due to contaminants transported from soil capillaries. Rice husk ash (RHA), disposed of in low-lying terrestrial cavities, also causes severe damage to the groundwater due to contaminant transport, which can seriously affect public and animal health (Santos et al. 2012).

The polluted water from rice mills primarily contains organic materials, total suspended solids (TSS), total dissolved solids (TDS), nutrients, pesticides, lignin, phenol, and pigment, which are attributable to large chemical oxygen demand (COD) values (Behera et al. 2010, Kumar et al. 2015). Lignin is a complicated, bio-refractory, and antagonistic substance in rice mill wastewater. Therefore, it creates problems in biological treatments of polluted water from rice mills (PWRM). The other substance contained in PWRM is phenol, which is also deleterious even at a low level and hampers the microorganisms (Kumar et al. 2015).

The amount of wastewater generated from a parboiled rice mill is nearly 20×10^6 liters annually in India (Varshney 2012). Thus, approximately 57,850 rice mills producing parboiled rice in India generate polluted water, approximately equal to $1{,}157 \times 10^9$ liters per year (CPCB 2008). Indian rice mills are of various types according to their production strength (Choudhary et al. 2015). Therefore, regulatory agencies of India for pollution control have furnished stringent guidelines about disposal standards of liquid rice mill effluent (CPCB 2008).

It is imperative to meet disposal standards set by CPCB for industrial wastewater. Hence, the essential treatment of the wastewater must be performed before discharging into water bodies (Mukherjee et al. 2015). According to India's Environment (Protection) Act (1986), each rice mill must establish a completely operational wastewater treatment plant (WWTP). The rice mill should also be accompanied by a biological remediation unit (CPCB 2007). However, owing to the investment required in establishing and maintaining WWTP, most stakeholders in this sector ignore the norms of CPCB (Business Standard 2015, Paul et al. 2015).

Several studies on research findings of the previous researchers on biological treatments of PWRM have been performed; each treatment technique has its own merits and demerits, and the acceptability of each method depends on various parameters viz., expenditures incurred, characteristics of the wastewater and the intended use of the treated water. In the present paper, efforts have been made to explicitly analyze their strategies and evaluate their research outcomes in terms of applicability, sustainability, feasibility, and techno-economic viability. This paper highlights anaerobic digestion, dark fermentation, microbial fuel cells, phytoremediation, and phycoremediation of wastewater from rice mills with the recovery of biomethane, biohydrogen, and bioelectricity as well as the removal of the organic and inorganic pollutants as well as nutrients like nitrogen and phosphorus.

PARBOILING PROCESS AND SOURCE OF POLLUTED WATER

Conventional techniques of partial boiling of paddy depend on the engineered operations adopted and range from one topographical vicinity to the other (Hettiarachchy et al. 2000). Parboiled edible rice is produced in rice mills and sold overseas from various international locations in Asia. They usually use partial boiling to avoid under-nourishment, food shortages, and wastage (Tomlins et al. 2005).

Parboiled rice production comprises some crucial stages. First, the paddy is soaked in water up to 23-31% moisture content. Heat treatment imparts gelatinization and enables dehydration of the paddy to an appropriate moisture stage suitable for milling operation. Different levels of heat treatment are needed for different partial boiling technologies, leading to parboiled rice production with different properties. The process must be improved to attain high yields and modify the quality of the product before establishing a rice mill (Bhattacharya 1985, Oli et al. 2014). Partially boiled rice is usually brown to yellow due to color dispersion from paddy husks. Moreover, it has high granular rigidity, making the least breakage during shelling and polishing operations difficult. It also has an enriched vitamin B content (Oli et al. 2014).

Paddy is screened to eliminate foreign substances such as grit, pebbles, and stones, as illustrated in Fig.1. The

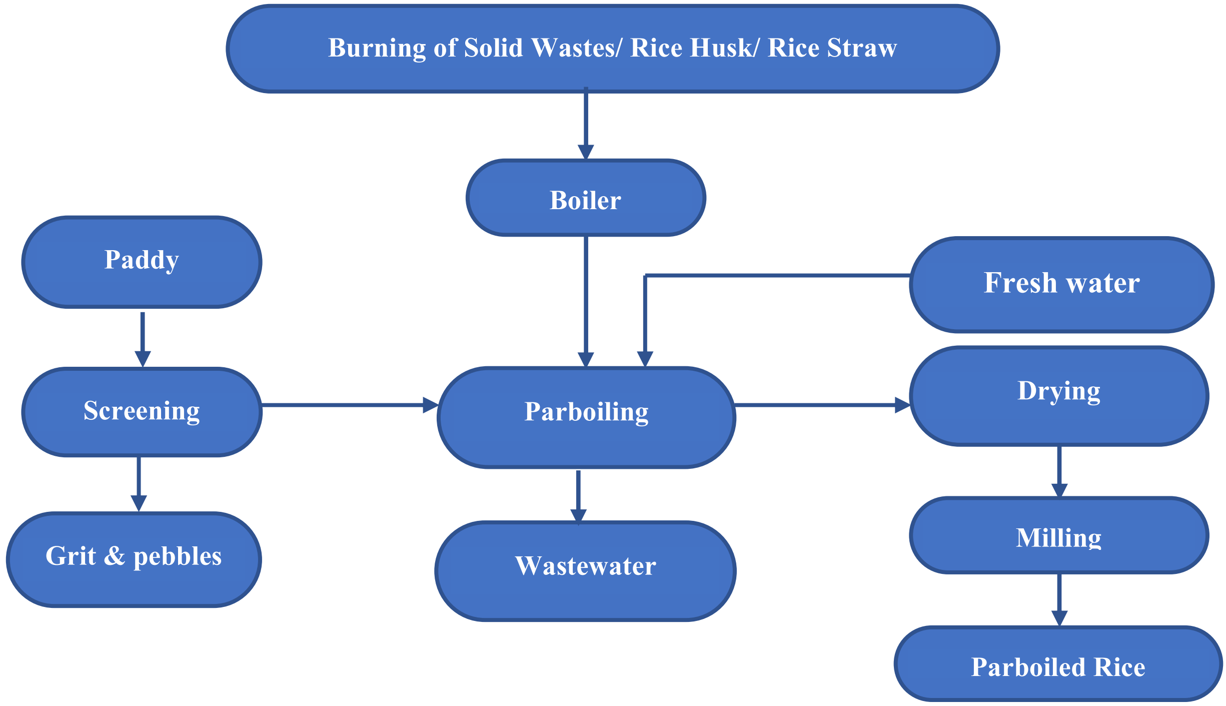

Fig. 1: Flow Diagram of parboiled rice mill processing and origin of PWRM (Asati 2013).

cleaned paddy is then placed into a drum-like vessel for partial boiling. Hot water vapor (steam) is introduced into the drum vessel, and the regenerated hot water is reused continually to ascertain a temperature of 70-100°C for 4 hours (Asati 2013). The parboiling process depends on seasonal variations. It is performed at 92-102°C during the humid rainy season and 72-82°C during summer's dry spell (Araullo et al. 1976). When partial boiling of the paddy is complete, the remaining water is extracted from the drum container. This water extracted from the parboiling unit is the PWRM. It contains organic and inorganic contaminants, including nutrients like nitrogen and phosphorus and bio-refractory organics like lignin and phenol.

Thus, the parboiling unit is the origin of PWRM. Though boiler blowdown is extracted from the same pipeline used for the liquid effluent discharge, its contribution is minimal, as boiler blowdown is generally accomplished every 2-3 months. Thus, the extracted wastewater from the parboiling unit is highly polluted and must be remediated before its discharge either into water bodies or onto the land surface. Where rice mills are far away from the surface water bodies like streams, lakes, and rivers, the wastewater is generally discharged onto the land surface. The source of wastewater generated from the rice milling industry and the processing technology of the parboiled rice mill are shown in Fig. 1.

Characterization of PWRM

The wastewater generated from rice mills contains various toxic organic materials and inorganic pollutants.

Table 1. illustrates the wastewater characterization of rice mills as previously quoted. The pH variation (4.5-8.5) is encountered due to the different characteristics of the paddy, the partial boiling procedure, and the water quality being adopted. However, the turbidity caused by the total suspended solids (0.3-166 $mg.L^{-1}$) enhances both chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which presents a significant challenge for water creatures by blocking sun rays and interfering with the photosynthetic process (Choudhury et al. 2010).

The wastewater produced primarily contains starch and other carbohydrates, lignin, phenol (C_6H_5OH), sulfates, chlorides, nitrates, total Kjeldahl nitrogen (TKN), phosphates, and some pigmenting substances that increase the BOD and COD of the wastewater (Behera et al. 2010). Lignin is a complicated and recalcitrant organic contaminant present in wastewater that hinders the biochemical reactions in the biological treatment of wastewater (Kumar et al. 2015). Phenol is also a virulent aromatic compound, even at small concentrations. Phytotoxicity testing of contaminated water from the rice mill has been performed on *Vigna radiata* (mung bean seeds), which have shown blocked roots and dwarf length of shoots (Kumar & Deswal 2020). Vigorous toxicological assays have been accomplished in *Lebistes reticulatus*-a, a fish variety, in terms of LC_{50} (deleterious concentration enough to take the life of half of the number of people residing in the affected area). The bioassay test reveals that the toxicity of PWRM to *L. reticulatus* depends upon the exposure time and strength of the wastewater. The anaerobically remediated PWRM is less toxic compared to raw wastewater. During the bio-assay test, the movement of *L. reticulatus* was drastically hindered (Giri et al. 2016). In addition, polluted water from rice mills has been reported to reduce the quality of sperm of zebrafish and, accordingly, lower reproductivity rates (Gerber et al. 2016). Consequently, the efficient and effective bioremediation of PWRM is necessary for safeguarding environmental and ecological sustainability.

ADVERSE IMPACT OF PWRM ON VARIOUS ECOSYSTEMS

The significant pollutions attributable to the rice mill industry are to the surface water, groundwater, soil, and air, but this paper emphasizes water pollution. The wastewater from rice mills has inverse impacts on the aquatic, terrestrial, and, ultimately, marine ecosystems. Accordingly, it has the potential to adversely influence the food chain as the pollutants may enter into aquatic and marine ecosystems. Moreover, pollutants added to surface water bodies like rivers and streams and terrestrial land due to untreated and undertreated rice mill wastewater disposal may worsen the water quality of surface and groundwater resources. The direct mixing of pollutants hampers surface water quality, whereas groundwater quality is rendered polluted due to contaminant transport. The wastewater produced by parboiled rice mills comprises high organic matter, nutrients, soluble solvents, pesticides, and phenolic contents (Gil de los Santos et al. 2012). The fish in the aquatic ecosystem may uptake these toxic contaminants. Eventually, they may enter the human and animal bodies in enlarged quantities due to biomagnification when they eat fish. Paul et al. (2015) assessed the impact of PWRM on surface water bodies. They obtained the concentrations of COD and

Table 1: Characterization of PWRM by previous researchers.

Sl. No.	pH	BOD [mg.L^{-1}]	COD [mg.L^{-1}]	TDS [mg.L^{-1}]	TSS [mg.L^{-1}]	Lignin [mg.L^{-1}]	Phenol [mg.L^{-1}]	Nitrogen [mg.L^{-1}]	References
1.	8.00	484	690	-	-	-	47	0.53	Pradhan and Sahu (2004)
2.	4.22-5.51	-	2,578-6,480	-	-	-	-	25-95	Queiroz et al. (2007)
3.	8.40	1,136	1,400	464	-	-	-	-	Manogari et al. (2008)
4.	-	-	5,020	-	-	-	-	-	Karnaratne (2009)
5.	4.00-4.30	-	2,200-2,250	-	-	80-88	15-17	-	Behera et al. (2010)
6.	7.50	1,200	1,350	700	1,100	-	-	-	Asati (2013)
7.	4.98	-	2,200	768	-	-	-	-	Karichappan et al. (2013)
8.	4.56	2,401	2,886	1,773	-	-	-	-	Choudhary et al. (2015)
9.	7.60	-	2,578-5,022	-	-	-	-	25.40-50.40	Bastos et al. (2015)
10.	4.70	1,089	1,931	3,010	-	-	-	36.70	Mukherjee et al. (2015)
11.	4.80	-	1,708	1,578	-	182	16.21	-	Kumar et al. (2016)
12.	4.67-4.90	3,968-4,464	6,400-7,200	1,386-2,340	4,187-5,134	-	-	62-80	Giri et al. (2016)
13.	5.10	6,900	18,600	4,720	-	-	-	31	Ramprakash & Muthukumar (2018)
14.	6.30	9,600	19,800	8,500	-	-	-	39	Rambabu et al. (2019)
15.	7.20	538	1,620	-	-	-	-	85	Keerthana et al. (2020)
16.	4.51 5.10	2,550-2,950	4,250-5,120	2,030-2,460	850-1,170	-	-	44-71	Sadhasivam & Jayanthi (2021)
17.	5.40	1,450	3,150	3,300	220	417	4.97	-	Raychoudhuri & Behera (2022)
18.	5.30	3,435	5,279	4,327	-	-	-	45	Anuf et al. (2022)
19.	5.40	1,350	2,800	3,300	-	-	4.95	-	Raychoudhuri et al. (2022)

BOD significantly more in downstream and drainage zones than in upstream samples.

Pradhan and Sahu (2011) examined the application of PWRM to irrigate rice fields. The wastewater was naturally alkaline (pH=8) and enriched with TSS, phenol, and BOD contents of 530, 35, and 450 $mg.L^{-1}$, respectively, with intermediate concentrations of TDS, COD, and phosphate of 670, 630, and 21 $mg.L^{-1}$, respectively. In this examination, the biomass growth, population, and reproduction of the earthworm *Drawida willsi* (Michaelsen) were assessed for 105 days with a sample time of 15 days. There are four main categories of earthworms prevailing in the cultivable land of India, but among them, *D. willsi* predominates, with greater than 80% concentration in biosolids (Pani 1986). The researchers found that the field irrigated by polluted rice mill water contained 22% fewer larvae than the field irrigated by normal river water.

Moreover, there was a diminution of 46% in the cocoon population. The researchers also revealed that the reproduction of cocoons diminishes by about 25% in the experimental plot compared to the control plot. The cocoon and worm populations diminished by about 41% and 26% in the experimental plot compared to the control plot.

BIOLOGICAL TREATMENT OF PWRM

The primary purpose of the biological treatment of PWRM is to reduce biodegradable organics, nutrients like nitrogen and phosphorus, and other contaminants to meet the effluent discharge standards of CPCB. Its secondary purpose is to achieve bioenergy in the form of biomethane, biohydrogen, and bioelectricity from agriculture-based industrial wastewater. Suppose bioenergy is exploited from agro-industrial effluents and other biomass at full capacity with the help of biological treatment. In that case, it can substantially reduce the dependency of energy requirements on fossil fuel-based thermal power plants. The global carbon footprint from the combustion of fossil fuels like coal, oil, and gas in 2021 is 36.4 billion metric tons, a major contributor to greenhouse gas (GHG) and global warming (USEPA 2022). Thus, biological treatment of biodegradable organic wastes with green energy retrieval is the probable domain that can generate wealth from wastes, diminish pollution loads in major environmental matrices- air, soil, and water, curtail global carbon emissions due to lesser dependence on thermal power plants for energy requirements and save the environment and ecological balance. Biological treatment may be categorized into three types:

- Microbial treatment
- Phytoremediation and
- Phyco-remediation

Microbial Treatment

A microorganism or microbe is a microscopic organism that is unicellular or multicellular. Microorganisms can be categorized as eukaryotes, prokaryotes, and viruses. The eukaryotes include protozoa, algae, fungi, and bacteria, whereas the prokaryotes include only bacteria and blue-green algae, also called cyanobacteria (Obayashi & Gaudy 1973). Thus, prokaryotes and bacteria are similar terms. Bacteria are unicellular, whereas algae and fungi are usually multicellular. Microbial treatment is a cumbersome process in which microbes, specifically bacteria, slowly degrade biodegradable and harmful organics and nutrients like nitrogen and phosphorus. Some protozoa and fungi also participate in the biodegradation process- aerobic and anaerobic. Microorganisms, except fungi, are generally sensitive to the substrate's pH, temperature, and alkalinity. Fungi are insensitive to pH variation and significantly survive even at diminished pH and low nitrogen levels.

Consequently, fungi are considered in wastewater treatment (Dadrasnia et al. 2017). Microbial treatment is currently quite common because of its simplicity in installation and operation and its generation of minimal toxic substances. It is a more efficacious and low-cost process as compared to physicochemical methods. It is mainly of three types: aerobic, anaerobic, and facultative. The aerobic process works in the presence of oxygen, the anaerobic process functions in the strict absence of oxygen, and the facultative process works both in the presence and absence of oxygen.

Microbial treatment of the polluted water emanating from rice mills may be subdivided into two categories:

- Anaerobic degradation
- Bioremediation with cyanobacteria and yeast

Anaerobic degradation (AD): Anaerobic degradation occurs in a strict anaerobic condition by anaerobic and facultative microorganisms. It is a biochemical reaction in four paramount stages: solubilization, acidogenesis, acetogenesis, and methanogenesis (Anukam et al. 2019).

***Solubilization*:** Complex organic molecules (carbohydrates, proteins, and lipids) are solubilized into monosaccharides (normal sugars), higher (long-chain) fatty acids, and amino acids.

Chemistry of solubilization-

$$(C_6H_{10}O_5)n + nH_2O \longrightarrow nC_6H_{12}O_6 + nH_2 \quad ...(1)$$

The solubilization of complex organic polymers takes place slowly. The rate and degree at which the polymers are solubilized depend on the following parameters:

- pH of the substrate
- Operational temperature of the anaerobic digester
- Particle size of the food
- Ingredients of the substrate, viz. carbohydrate, protein, lipids, and lignin contents
- The concentration of solubilization products viz. volatile fatty acids (VFA)
- Ammonia nitrogen (NH_4^+-N) concentration
- Hydraulic retention time (HRT) and solids retention time (SRT) of the substrate in the digester

***Acidogenesis*:** It is the fermentative phase, in which the simple and soluble molecules obtained in solubilization are decomposed into carbon dioxide and hydrogen gas by acidogenic bacteria. The essential acid in this phase is acetic acid (CH_3COOH), the most important organic acid used as a substrate by bacteria that generate methane (CH_4) gas.

Chemistry of acidogenesis:

$$C_6H_{12}O_6 + 2H_2 \longleftrightarrow 2CH_3CH_2COOH + 2H_2O \quad \ldots(2)$$

$$C_6H_{12}O_6 \longrightarrow 3CH_3COOH \quad \ldots(3)$$

$$C_6H_{12}O_6 \longleftrightarrow 2CH_3CH_2OH + 2CO_2 \quad \ldots(4)$$

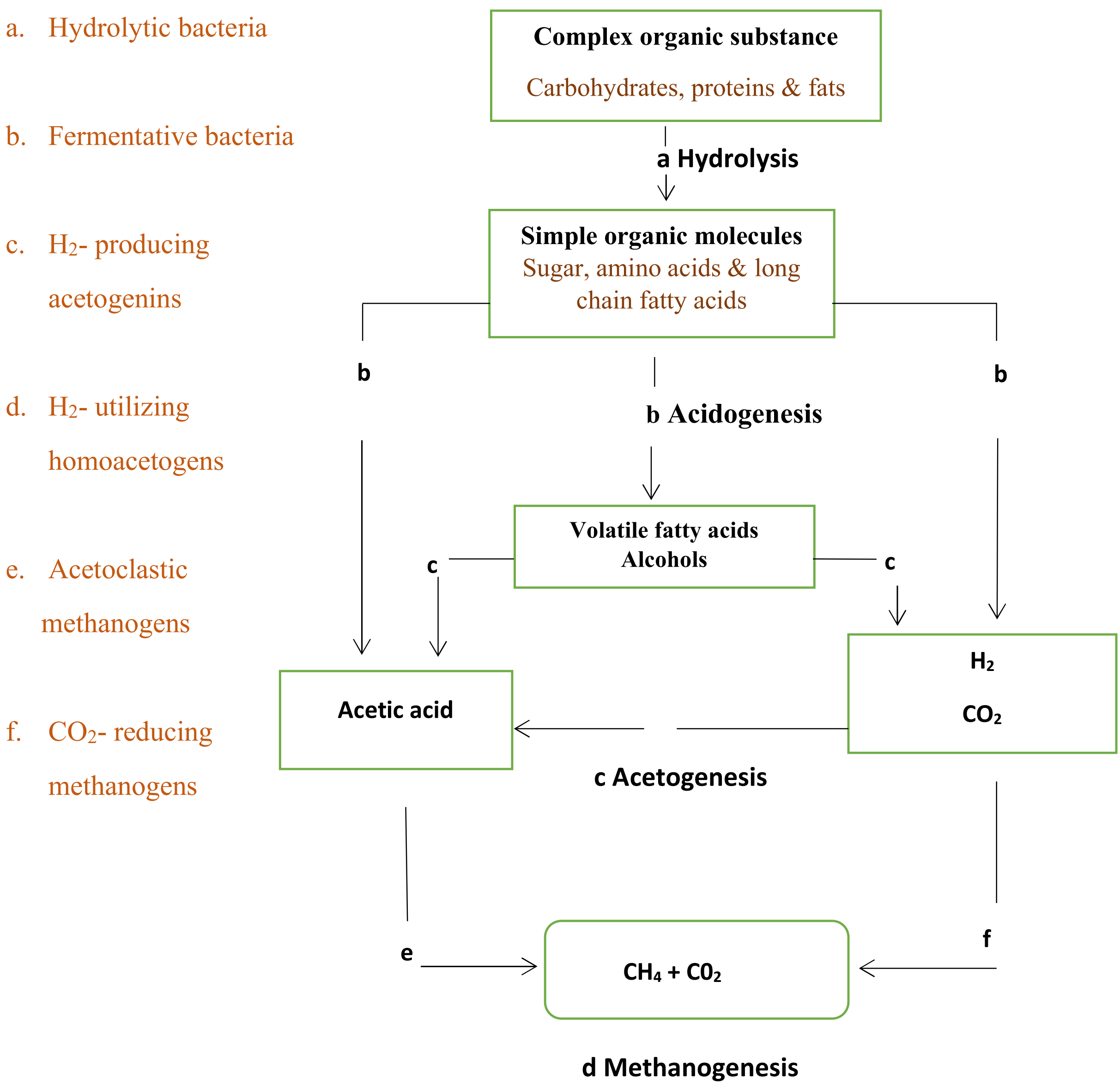

Fig. 2: Flow chart of the anaerobic digestion process (Anukam et al. 2019).

***Acetogenesis*: ** In this phase, simpler molecules made by the acidogenic bacteria are converted into acetic acid, CO_2 and H_2 gases by acetogenic bacteria. This phase is also referred to as dehydrogenation, as the waste of acetogenesis is H_2 gas formed in the acidogenic phase.

Chemistry of acetogenesis -

$$C_6H_{12}O_6 + 2H_2O \longleftrightarrow 2CH_3COOH + 2CO_2 + 4H \quad ...(5)$$

$$CH_3CH_2OH + 2H_2O \longleftrightarrow CH_3COO^- + 3H_2 + H^+ \quad ...(6)$$

$$CH_3CH_2COO^- + 3H_2O \longleftrightarrow CH_3COO^- + H^+HCO_3^- + 3H \quad ...(7)$$

***Methanogenesis*: ** It is the final stage of the anaerobic degradation procedure, in which methanogenic bacteria convert intermediate products of the previous phase, namely acetic acid and hydrogen gas, into methane, CO_2 and water. Methanogens are frequently anaerobes, and their vulnerability is exceptionally high to little oxygen.

Chemistry of Methanogenesis -

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \quad ...(8)$$

$$CH_3COOH \longrightarrow CH_4 + CO_2 \quad ...(9)$$

$$2CH_3CH_2OH + CO_2 \longrightarrow CH_4 + 2CH_3COOH \quad ...(10)$$

The methanogenic stage is highly vulnerable to high and low pH and strictly takes place in between a pH range of 6.5 to 8.

The anaerobic digestion process is illustrated in Fig. 2.

Rajesh et al. (1999) examined the effectiveness of bioreactors for remediating PWRM. The biodigester used a two-phase bio-methanation procedure employing up-flow anaerobic sludge blanket (UASB) digesters. The efficiencies of removal of BOD and COD were 89% and 78% in the organic loading rate (OLR) of 3 kg $COD.m^{-3}.day^{-1}$. However, this strategy requires further research to be applied in this field.

Lopes et al. (2001) conducted successful experimentation on the denitrification of parboiled rice mill wastewater over a UASB reactor, which creates an anoxic environment. It eradicated the need for an extra digester for denitrifying the wastewater. In addition, the digestion procedure exhibited 80% removal of total nitrogen.

Saini et al. (2016) performed anaerobic treatment of PWRM at room temperature in a lab-scale cylindrical glass UASB reactor with a 2.4-liter reaction volume. The length and diameter of the reactor were 60 cm and 24 cm, respectively. The target substrate was co-digested with filtrate of biogas plant sludge and distilled water in the ratio of 2:1:1. The researcher observed COD removal efficiencies to be more than 97%, 89%, and 86% in phases I, II, and III, respectively, along with the production of biomethane. Studies show that anaerobic digestion is an excellent option to treat rice mill wastewater since 86% COD removal was attained even with a high dose of organic loading, i.e., 100% influent concentration and HRT of 10 hrs.

Sadhasivam & Jayanthi (2021) performed anaerobic treatment of rice mill wastewater (75%) co-digested with distillery sludge (25%) in a lab-scale setup of a constantly stirred anaerobic tank reactor at ambient temperature. The researchers observed that % COD reduction efficiency of 91% was attained at an HRT of 32 days and an OLR of 3.75 kg $COD.day^{-1}.m^{-3}$. The researchers suggest that anaerobic degradation is an appropriate method for the abatement of polluted rice mill water with substantial diminution in COD and resource recovery as methane gas. Studies reveal that a small OLR and considerable HRT provide excellent BOD and COD removal efficiencies as well as continuous and high biomethane yields.

Bioremediation with cyanobacteria and yeast: Cyanobacteria are photosynthetic and aquatic. They produce their food in sunlight and live in water. They are tiny and often do not coalesce as bacteria, although they usually grow into colonies large enough to be visible. They differ from prehistoric fossils, dating approximately 3500 million years ago (Whitton & Potts 2012). Since they are water-living microorganisms and photosynthetic, they are often called "blue-green algae." However, there is no correlation between cyanobacteria and other aquatic microorganisms like algae.

Queiroz et al. (2007) treated the PWRM with the help of cyanobacteria *Aphanothece microscopica Nageli* in an agitated biodigester in the batch mode. The dynamic analysis is assessed by 83.44% and 72.74% removal of COD and total nitrogen (Total-N), respectively, after 15 h of HRT. Santos et al. (2012) treated the PWRM with a methylotrophic yeast *Pichiapastoris X-33* in a growth media of 15 grams per liter ($g.L^{-1}$) of biodiesel-derived glycerol. It exhibited a 55%, 45%, and 52% reduction in COD, TKN, and orthophosphate phosphorus (PO_4^{3-}- P) and recovered 2.1 $g.L^{-1}$ of the useful biomass.

Manogari et al. (2008) carried out an appraisal investigation on the PWRM by using immobilized cells of a cyanobacterial strain, namely *Pseudomonas species*, belonging to the family Pseudomonadacea, in a packed bed reactor. The investigation exhibited a reduction of 86.44%, 55.34%, 78.07%, 76.36%, and 76.51%, respectively, in COD, BOD, electrical conductivity (EC), salinity, and TDS, in an HRT of 24 hours.

Merits of Microbial Treatment

a. Cost-effective and minimal energy requirement
b. Biodegradability of the substrate depends upon the BOD/COD ratio
c. Eco-friendly and non-lethal
d. Substantial diminution in hazardous components of the wastewater
e. Recovery of biomethane as a by-product

Demerits of Microbial Treatment

a. The operation time of the bioreactor is high
b. Nuisance and odor problems in anaerobic digestion
c. High dependency on pH, temperature, alkalinity, and presence of VFA
d. Contaminant reduction largely depends on carbon-nitrogen (C/N) and phosphorus-nitrogen (P/N) ratios

Phytoremediation

Phytoremediation is a growing technology for the treatment of polluted water. The process requires plants to degrade, mitigate, transport, or stabilize the pollution potential in water, soil, and sludge (Kumar & Deswal 2020). Certain plants diminish organic matter, heavy metals, and nutrients from water and wastewater (Pavlineri et al. 2017). It is an inexpensive and power-efficient procedure that effectively removes contaminants from contaminated water.

Mukherjee et al. (2015) investigated the treatment of PWRM and concluded that the proliferation of *Pistia stratiotes L.* (water lettuce) was hindered in the wastewater without dilution. Subsequently, the researchers diluted the PWRM with fresh water in a ratio of 1:1. They found that removal efficiencies of BOD, total phosphorus (Total-P), and nitrate nitrogen (NO_3-N) were 83–85%, 71–73%, and 68– 70%, respectively with an HRT of 15 days after adopting the dilution strategy.

Kumar & Deswal (2020) conducted an extensive study on the treatment of PWRM with the help of four water plants, salvinia, water lettuce, duckweed, and water hyacinth, and got an inspiring outcome. The plants diminished COD and Total-P to 75% and 80% during the investigation for 15 days. As a result, some investigators are exploring the actual application of water plants to remediate contaminated water, in which they have obtained motivating outcomes.

Ajayi & Ogunbayio (2012) used water hyacinth to eliminate contaminants from wastewater from the textile, pharmaceutical, and metal industries. Lead elimination by duckweed was studied by Singh et al. (2012). Azeez & Sabbir (2012) also studied the strength of duckweed in removing pollutants from polluted water of petrochemical industries. Favas & Pratas (2013) conducted a comprehensive study on removing uranium through water plants. The elimination of heavy metals from polluted water of paper mills by aquatic plants was evaluated by Mishra et al. (2013). Abu Bakar et al. (2013) studied the elimination of arsenic, aluminum, and zinc from polluted water of goldmines using water plants. The elimination of pollutants from polluted water of sugar mills by water plants was explored by Reddy et al. (2015). The potential use of water hyacinth in removing chromium from sewage was explored by Saha et al. (2017). An extensive study on the bioremediation of landfill leachate by duckweed was conducted by Daud et al. (2018).

Merits of Phytoremediation

a. It can be applied at the micro level, even in a water tub, as a pilot project
b. Sustainable, cheaper, and simpler biological method
c. Biomass can be harvested and applied in other aerobic and anaerobic reactors
d. Eco-friendly and zero energy-consuming method

Demerits of Phytoremediation

a. Large operation time, as the plants need time to grow and absorb the pollutants of the wastewater
b. Plants' growth is hindered in the PWRM without dilution since high concentrations of hazardous materials may be toxic to the plants.
c. The depth of the treatment zone is determined by the root zone depth of the plants used in the phytoremediation process.

Phycoremediation

Phycoremediation is the utilization of microalgae or macroalgae to reduce or bio-transform the contaminants, inclusive of hazardous synthetics as well as nutrients from contaminated water. It is considered an eco-friendly technique in the bioremediation of polluted water. In wastewater, ammonia is the predominant inorganic nitrogen, and algae help convert inorganic nitrogen into organically bound nitrogen by physiological ingestion. The functioning of algae in the bioremediation of polluted water depends on various factors, namely features of wastewater, the intensity of solar insolation, ambient CO_2 gas, and N/P & C/N ratios (Hongyang et al. 2011). The bioremediation of wastewater by microalgae was first investigated during the 1950s (Johansen 2012). After this investigation, the correlation between microalgae and bacteria was found in 1957 (Oswald et al. 1957).

Phycoremediation incorporates algal treatment as a biological method to sustainably facilitate the treatment of polluted water with green energy retrieval. Microalgae, the heterotrophic and photosynthetic microorganisms, can remediate polluted water by taking excessive pollutants and nutrients (Wang et al. 2012, Solovchenko et al. 2014). Phycoremediation is a cost-effective and efficacious method for remediating nutrient-laden wastewater from industries such as tanneries, textiles, carpet milling, and food processing, where a substantial elimination of nutrients and biomass production is visualized to occur (Pathak et al. 2014, Fazal et al. 2018).

A lot of investigators have investigated the capability of microalgae/algae to remediate polluted water. Abinandan et al. (2015) studied bioremediation of the PWRM by *Chlorella pyrenoidosa* and *Scenedesmus abundans* in a 500-mL Erlenmeyer flask comprising 300 mL of contaminated water under irradiation of a flashlight having an intensity of illumination of 1800 lux. The outcomes achieved in this investigation illustrated a significant elimination of PO_4^{3-}- P and NH_3-N to 97% and 91%, respectively. Kim et al. (2010) carried out an extensive study on nutrient removal from the PWRM by a species of green microalgae *Chlorella vulgaris* in a batch reactor with an HRT of 9 days and obtained 55.8% of NH_3-N removal. The biodegradation of secondary effluent by Cyanobacterium *Phormidium bohneri* was accomplished in a batch reactor for an HRT of 5 days (Laliberte et al. 1997). The researchers found that the cyanobacterium removed PO_4^{3-}- P and NH3-N, 1.6-13.8 $mg.L^{-1}.day^{-1}$ and 2.4-19.9 $mg.L^{-1}.day^{-1}$, respectively.

Umamaheshwari & Shanthakumar (2020) studied the growth of five microalgal species using response surface methodology (RSM) in the PWRM viz. *Chlorella vulgaris* (Cv), *Chlorella pyrenoidosa* (Cp), *Spirulina* sp. (Ss), *Scenedesmus obliquus* (So) and *Scenedesmus abundans* (Sa). Better biomass production and substantial wastewater

Table 2: Evaluation of various biological treatment processes for PWRM.

Sl. No.	Method	Brief-description	Result	Reference
1.	Phycoremediation (*Chlorella pyrenoidosa*)	Research works performed on raw PWRM and autoclaved PWRM. Light illuminance = 1800 lumen/m^2	Pollutants reduction: Raw PWRM = 97.5% Autoclaved PWRM = 97.7% NH_3-N reduction: Raw PWRM = 90.3% Autoclaved PWRM= 91.4%	Abinandan et al. (2015)
2.	Phyco-remediation (*Scenedesmus abundans*)	Research works performed on raw PWRM and autoclaved PWRM. Light illuminance = 1800 lumen.m^{-2}	Pollutants reduction: Raw PWRM = 98.3% Autoclaved PWRM = 98.7% NH_3-N reduction: Raw PWRM = 92% Autoclaved PWRM = 90%	Abinandan et al. (2015)
3.	Phytoremediation	Water lettuce (*Pistia Stratiotes*) applied in 1:1 diluted PWRM with tap water; plant growth hindered in undiluted ww	Pollutants reduction: COD = 65% NH_3-N = 98% NO_3-N = 70% Phosphates = 65%	Ramprakash & Muthukumar (2015)
4.	Phytoremediation	Four hydrophytic plants, viz., water lettuce, water hyacinth, salvinia, and duckweed, were applied in 1:1diluted PWRM with tap water	Pollutants reduction: Total-P = 80% COD = 75% Operation time = 15 days Max. removal efficiency shown by water lettuce	Kumar & Deswal (2020)
5.	Dark fermentation	Nickel oxide (NiO) and cobalt oxide (CoO) nanoparticles included in the dark fermentation process of PWRM	NiO NPs (nanoparticles) increased biohydrogen production by 2.1 to 2.4 times; CoO NPs increased biohydrogen production by 1.9 to 2.0 times	Rambabu et al. (2021)
6.	Dark fermentation	Combined methods of dark fermentation and Electro-fermentation adopted for PWRM	41% more hydrogen production compared with dark fermentation alone	Ramprakash et al. (2021)
7.	Anaerobic digestion	75% PWRM+ 25% distillery sludge used in an anaerobic batch reactor	COD reduction = 91%	Sadhasivam & Jayanthi (2021)

Table 3: Economic efficiency and suitability of different biological treatment methods for PWRM.

Sl. No.	Method	Capital Requirement	HRT	Value addition	Effluent Quality
1.	Microbial treatment	Medium	Large	Biomethane in anaerobic process Biohydrogen in the dark fermentation process Bioelectricity in microbial fuel cells	Medium to good
2.	Phytoremediation	Small	Large	Biomass	Inferior
3.	Phyco-remediation	Small	Large	Biomass	Inferior

abatement were obtained by 30% inoculum size at 25°C. *Chlorella pyrenoidosa* showed a high content of dry biomass (831 mg.L^{-1}) and over 90% uptake of PO_4^{3-}- P and NH_3-N out of all chosen microalgae. Similar results were obtained for *Chlorella vulgaris* and *Scenedesmus obliquus,* with a more than 80% removal potential. Moreover, *Chlorella pyrenoidosa* showed the best result at a higher temperature. In contrast, other species failed to sustain biomass generation and the elimination of PO_4^{3-}-P and NH_3-N. The growth pattern for microalgae was in the descending order of Cp > Cv > So > Sa > Ss in the PWRM. This study has justified that phycoremediation may be an effective wastewater treatment method while selecting the appropriate species and conditions indispensable for grade-up applications.

Merits of Phycoremediation

a. Retrieval of valuable by-product
b. Biodegradability is significantly achieved
c. Eco-friendly and non-toxic
d. There is no requirement for any chemical to be added
e. Low installation and operation cost

Demerits of Phycoremediation

a. High dependency on pH, temperature, alkalinity, and the presence of VFA
b. Large operation time
c. Pollutant removal is highly dependent on light, C/N, and P/N ratios.

According to the literature on the biological treatment methods of PWRM, we can conclude that each method has its own merits and demerits. Hence, the adoption of the appropriate method depends on the use of the treated effluent. If the treated effluent is proposed for irrigation, slightly inferior-quality effluent may be used. On the contrary, if the effluent is intended to be used for cattle farming or recycling for the parboiling operation unit in the rice mill itself, we may go for physicochemical treatment methods, viz., adsorption by chitosan and electrocoagulation, where effluent quality is superior. However, physicochemical treatment methods have their drawbacks of being costly and generating a huge amount of sludge, whose safe disposal is a big concern. Table. 3. reveals the criteria for economic efficiency and suitability of different biological treatment methods of PWRM. The following inferences can be concluded from the literature.

- Phytoremediation is favorable for small enterprises and household wastewater treatment systems. It is an energy-saving and non-polluting biological method advantageous for countryside areas, where sufficient land is not a big problem. It is a time-consuming method and requires a sizable land area. The growth of the hydrophytic plants in undiluted PWRM is impeded due to excessive concentration of the pollutants and low pH value. Therefore, it is suggested that the wastewater must be blended with fresh tap water before treatment by phytoremediation technique. However, this technique is unable to treat wastewater containing radioactive pollutants.

  The quality of the effluent by this technique is a bit inferior. Consequently, treated effluent by this method is not safe for cattle farming. Rather, it is quite safe for irrigating crops. The researchers should open new avenues for integrating microorganisms with phytoremediation to improve effluent quality.

- Phycoremediation is also efficacious for micro-industrial and household wastewater remediation. Like phytoremediation, it is an environment-friendly, non-polluting, and non-toxic method. The microalgae and algae are chlorophyll-rich, photosynthetic, and single-celled tiny hydrophytes. They significantly reduce nutrients like nitrogen and phosphorus, BOD, COD, and other toxic contaminants, but they moderately enhance total solids (TS) by the microalgal growth. The nutrient removal efficiency of phytoremediation is 78% to 99%, whereas BOD and COD removal efficiencies are 40% to 65%. However, overall effluent quality by this method is slightly inferior. Consequently, effluent from this technique should also be encouraged for irrigation purposes.

- Microbial treatment is a cost-effective, environment-friendly, and non-lethal method. It facilitates enhanced efficiency in removing volatile substances (organic materials) and leaves a smaller carbon footprint. Anaerobic digestion depends upon pH, temperature, alkalinity, VFA, C/N ratio, and P/N ratio. Aerobic digestion is an energy-intensive biodegradable process requiring energy for aerating the bioreactor. Anaerobic digestion is an energy-saving process in which aeration is not required as anaerobes strictly work without oxygen. Anaerobic digestion contributes to the value addition in the form of biomethane as a by-product. The effluent quality of microbial treatment is medium to good. Therefore, the effluent from the microbial treatment process may be used for cattle farming and recycling to the parboiling unit in the rice mill after slight physicochemical treatment, like adsorption by chitosan or electrocoagulation.

VALUE ADDITION FROM PWRM

Technology has radically changed in treating polluted water from various industries, including rice mills and other agro-industries. However, the stakeholders of this pertinent sector in previous times merely intended to eliminate pollutants from wastewater. But nowadays, this notion has changed. They aspire to create wealth from waste. They are trying to restore value-added products with reduced energy consumption due to breakthroughs in microbiological science and biotechnology. These retrieval techniques are referred to as water resource recovery facilities (WRRFs), according to Gude et al. (2016).

The concerns for the environment emphasize recycling industrial wastes along with the retrieval of valuable products. Recycling waste is also essential for a sustainable environment and the economy since it compensates the expenditures incurred on the operation and maintenance of WWTP by generating green energy. Therefore, the future use of polluted water for retrieving enormous amounts of valuable products is gaining momentum day by day.

The prime purpose of traditional treatment plants for polluted water is to eliminate impurities from the wastewater aimed at meeting disposal regulations and stabilizing the sludge aftermath. However, the ongoing decline in conventional energy sources, the ecological imbalance caused by enhanced pollution load on the environment, and the insufficient availability of water resources necessitate appropriate endeavors to achieve sustained ecosystems. The conversion of wastewater and sludge into bioenergy is an innovative technology of non-conventional energy sources with the help of microorganisms, whose ultimate aim is to diminish the discharge of non-reclaimed wastes into the environment.

Microbial Fuel Cell (MFC)

MFC is a modern technology that generates bioelectricity with the aid of exoelectrogen bacteria while removing pollutants from medium to high-strength wastewaters (Pant et al. 2010, He et al. 2015). It is an electro-biochemical device in which electrical energy is generated by microbes that accomplish the anaerobic degradation of organic materials. Microbes oxidize organic materials to generate protons and electrons in the anodic chamber, and bioelectricity is generated due to the release of electrons. Carbon dioxide (CO_2) gas and biomass are also released due to the biochemical reactions involved in this bio-assay procedure. Behera et al. (2010) have used PWRM as a viable substrate to prepare MFC for generating bioelectricity and removing pollutants from wastewater. Researchers have achieved remarkable outcomes of earthen container MFC concerning bioelectricity generation and abatement of organics from the PWRM.

Raychoudhury & Behera (2020) revealed that the main hurdle in achieving higher production from MFC is the loss of organics due to methanogenesis. Hence, coulombic efficiency (CE) can be increased by regulating methanogenesis. The researchers compared the effect of three inoculum treatment techniques viz. thermal treatment (MFC_t), ultrasonic treatment (MFC_u), and aeration (MFC_a) for controlling methanogenesis using PWRM as the substrate of MFC. MFC_t, MFC_u, and MFC_a gave power densities of 309.19 $mW.m^{-3}$, 525.62 $mW.m^{-3}$ and 656.10 $mW.m^{-3}$ respectively. Thus, MFC_u and MFC_a gave 1.7 and 2.1 times higher power densities than MFC_t. Similarly, MFC_t, MFC_u, and MFC_a exhibited CE of 9.27%, 14.14%, and 17.21%, respectively. The researchers concluded that intermittent aeration by air exposure of inoculum was observed to be more beneficial for bioelectricity generation in MFC.

Raychoudhury & Behera (2021) explored acidogenic pretreatment to the PWRM to increase the generation of bioelectricity as well as substrate removal efficiency of the MFC. The researchers acidified the PWRM in the acidogenic chamber to promote the biodegradation of complex organics before feeding it to MFC. They compared the performance of the acidogenic chamber-MFC unit (MFC-Acid.) with a conventional dual-chambered MFC (MFC-Con.) for an HRT of 15 days. The average COD removal efficiency for MFC-Acid. And MFC-Con. HRT of 15 days was 74.96 ± 0.98% and 70.71 ± 1.24%, respectively, under steady-state conditions. The higher COD removal efficiency in the former case was achieved due to acidogenic pretreatment, which facilitated the conversion of complex organics into simpler compounds. Similarly, the maximum volumetric power density was obtained in MFC-Acid. MFC-Con. were 2.34 ± 0.07 $W.m^{-3}$ and 2.11 ± 0.04 $W.m^{-3}$, respectively under the steady-state condition.

Biohydrogen and Methane Generation

Hydrogen is an eco-friendly, energetic, non-conventional, and reclaimable propellant with tremendous energy. According to Demirbas et al. (2011), hydrogen burns vigorously to produce 2.75 times more energy than petrochemicals, and, in this combustion, water is the only final product. Hydrogen gas is considered a superior alternative to fossil fuels due to its specific characteristics of the highest gravimetric energy density (i.e., 120 $kJ.g^{-1}$), zero carbon emission on the ignition, and substantial energy-transmitting efficiency (Rambabu et al. 2019). Wang et al. (2011) generated hydrogen gas (H_2) and CH_4 from industrial wastewater and municipal sewage by fermentation techniques in two phases, along with contaminants removal aimed at providing economic development potential for waste management.

PWRM comprises a large amount of biodegradable organic materials like starch, cellulose, and hemicellulose, so it is one of the efficient and renewable bioresources for the generation of biohydrogen (Ramprakash & Muthukumar 2014). Peixoto et al. (2012) produced hydrogen and methane from PWRM by fermenting wastewater with microflora in two phases.

Ramprakash & Muthukumar (2015) produced bio-hydrogen from starch-rich PWRM using *Klebsiella aerogenes* (also known as *Enterobacter aerogenes*) and *Citrobacter freundii* (a species of *Enterobacteriaceae* family). The results reveal effective enzymatic hydrolysis with a reduction in COD of 71.8%. In addition, a substantial amount of hydrogen was produced through a combination of acid and enzymatic processes. Furthermore, the researchers ameliorated bio-hydrogen generation through a mutant strain of *Enterobacter aerogenes* compared with the indigenous species.

Rambabu et al. (2021) investigated that biohydrogen production was enhanced by introducing nickel oxide (NiO/26 nm) and cobalt oxide (CoO/50 nm) nanoparticles (NPs) at a concentration of 1.5 $mg.L^{-1}$ to dark fermentation of PWRM using *Clostridium beijerinckii* DSM 791- a gram-positive, rod-shaped and motile bacteria of the genus *Clostridium*. Biohydrogen generation was enhanced by 2.09 and 1.9 times for optimum dosage (1.5 $mg.L^{-1}$) of NiO and CoO, respectively, compared with the control run without NPs. COD removal efficiencies of 77.6% and 69.5% were obtained for NiO and CoO nanoparticles (NPs), significantly more than the control run without NPs (57.5%). Thus, including NiO and CoO NPs in wastewater fermentation is a good technique for enhanced biohydrogen production.

In the future, there is enormous potential to remove pollutants from wastewater and, at the same time, produce bioenergy by dint of biological treatments. However, obtaining significant levels of efficiency and productivity are major threats to be tided over to allow for effective implementation.

CONCLUSION

The rice milling industry must comply with the strict effluent discharge standards and maintain human health and environmental sustainability. Effective wastewater treatment and safe disposal of the sludge produced are essential for this. However, the rice millers are not complying with the effluent discharge norms of CPCB satisfactorily due to the excessive expenditures incurred on it. So, the current challenge is to enunciate an economical and affordable method for the sustainable treatment of PWRM. The favorable results of biological treatment techniques remain in generating fewer wastes, reducing harmful chemicals, and converting waste into valuable resources. This paper discusses three techniques for the biological treatment of PWRM: microbial treatment, phytoremediation, and phycoremediation. Phytoremediation and phycoremediation have also emerged as cost-effective and non-polluting techniques for the remediation of PWRM. Phycoremediation may be encouraged in a small community at grass root levels. The treated water by biological treatment methods may be used for irrigating crops, fisheries, and other aquacultural practices for sustainable water management. The authors conclude that future research should focus on developing novel and innovative biological treatments for wastewater, including PWRM. In addition, it should focus on reducing massive sludge production, retrieving precious by-products, and conserving ecological balance.

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REFERENCES

Abinandan, S., Bhattacharya, R. and Shanthakumar, S. 2015. Efficacy of chlorella pyrenoidosa and *Scenedesmus abundans* for nutrient removal in rice mill effluent (paddy-soaked water). Int. J. Phytoremed., 17(4): 377-381.

Abu Bakar, A.F., Yusoff I., Fatt, N.T., Othman, F. and Ashraf, M.A. 2013. Arsenic, zinc, and aluminum removal from gold mine wastewater effluents and accumulation by submerged aquatic plants (*Cabomba piauhyensis*, *Egeria denser*, and *Hydrilla verticillata*). Biomed. Res. Int., 13: 890803.

Ajayi, T.O. and Ogunbayio, A.O. 2012. Achieving environmental sustainability in wastewater treatment by phytoremediation with water hyacinth (*Eichhornia crassipes*). J. Sustain. Dev., 5(7): 8.

Alderson, M.P., Santos, A.B.D. and Filho, C.R.M. 2015. Reliability analysis of low-cost, full-scale domestic wastewater treatment plants for reuse in aquaculture and agriculture. Ecol. Eng., 82: 6-14.

Anuf, A.R., Ramaraj, K., Sivasankarapillai, V.S., Dhanusuraman, R., Maran, J.P., Rajeshkumar, G. and Díez-Pascual, A.M. 2022. Optimization of electrocoagulation process for treatment of rice mill effluent using response surface methodology. J. Water Process Eng., 49: 103074.

Anukam, A., Mohammadi, A., Naqvi, M. and Granstrom, K. 2019. A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency. Processes, 7(8): 504.

Araullo, E.V., De Pauda, D.B. and Graham, M. 1976. Rice: Post Harvest Technology. International Development Research Centre, Ottawa, Canada, pp. 163-204.

Asati, S.R. 2013 Treatment of wastewater from parboiled rice mill unit by coagulation/flocculation. Int. J. Life Sci. Biotechnol. Pharm. Res., 2: 264-277.

Azeez, N.M. and Sabbir, A.A. 2012. Efficiency of duckweed (Lemna minor L.) in phytoremediation of wastewater pollutants from Basrah oil refinery. J. Appl. Phytotechnol. Environ. Sanit., 1(4):163-172.

Bastos, R.G., Bonini, M.A., Zepka, L.Q., Jacob-Lopes, E. and Queiroz, M.I. 2015. Treatment of rice parboiling wastewater by cyanobacterium *Aphanothece microscopica* Nägeli with potential for biomass products. Desal. Water Treat., 56(3): 608-614.

Behera, M., Jana, P.S., More, T.T. and Ghangrekar, M.M. 2010. Rice mill wastewater treatment in microbial fuel cells fabricated using proton exchange membrane and earthen pot at different pH. Bioelectrochemistry, 79: 228-233.

Bhattacharya, K.R. 1985. Parboiling of rice. In: Juliano, B.O. (ed), Rice: Chemistry and Technology, Second Edition, American Association of Cereal Chemists, St. Paul, pp. 289-348.

Bhattacharya, K.R. 2011. Rice Quality. Woodhead Publishing Limited, Cambridge, UK.

Business Standard 2015. Rice Mills: HC Refuses to Extend Deadline for Getting Pollution. Press Trust of India, Chennai (Accessed on 29.01.2022).

Central Pollution Control Board (CPCB) New Delhi 2007. Guidelines on Effluent Characteristics (Accessed on 17.01.2022).

Central Pollution Control Board (CPCB) 2008. Comprehensive Industry Documents On The Pulse, Wheat, And Rice Mills. Ministry of Environment and Forest. Govt. of India Report, New Delhi, p. 76.

Choudhary, M., Majumder, S. and Neogi, S. 2015. Studies on the treatment of rice mill effluent by electrocoagulation. Sep. Sci. Technol., 50: 505-51.

Chowdhury, P., Viraraghavan, T. and Srinivasan, A. 2010. Biological treatment processes for fish processing wastewater: A review. Bioresour. Technol., 101: 439-449.

Dadrasnia, A., Usman, M. M., Lim, K. T., Velappan, R. D., Shahsavari, N., Vejan, P. and Ismail, S. 2017. Microbial Aspects in Wastewater Treatment–A Technical. Environmental Pollution and Protection, 2(2): 75-84.

Daud, M.K., Ali, S., Abbas, Z., Zaheer, I.E., Riaz, M.A., Malik, A., Hussain, A., Rizwan, M., Zia-ur-Rehman, M. and Zhu, S.J. 2018. The potential of duckweed (Lemna minor) for the phytoremediation of landfill leachate. J Chem., 2018: 1-9.

Demirbas, A., Balat, M. and Balat, H. 2011. Biowastes-to-biofuels. Energy. Convers. Manage 52: 1815-1828.

Department of Commerce & Industries, Chhattisgarh 2022. https://industries.cg.gov.in

Favas, P.J.C. and Pratas, J. 2013. Uptake of uranium by native aquatic plants: potential for bioindication and phytoremediation. E3S Web Conf 1: 2-4.

Fazal, T., Mushtaq, A., Rehman, F., Khan, A. Ullah, Rashid, N., Farooq, W., Rehman, M.S.U. and Xu J. 2018. Bioremediation of textile wastewater and successive biodiesel production using microalgae. Renewable Sustainable Energy Rev., 82 (Feb): 3107-3126.

FNB (Food and Beverages) News 2022. Rice Processing and Value Addition in India FB http://www.fnbnews.com

Galvez, J.M., Gomez, M.A., Hontoria, E. and Gonzalez-Lopez, J. 2003. Influence of hydraulic loading and air flow rate on urban wastewater nitrogen removal with the submerged fixed-film reactor. J. Hazard. Mater., 101(2): 219-229.

Gerber, M.D., Junior, A.S.V., Caldas, J.S., Corcini, C.D., Lucia, T. Jr., Correa, L.B. and Correa É.K. 2016. Toxicity evaluation of parboiled rice effluent using sperm quality of zebrafish as bioindicator. Ecol. Indic., 61: 214-218.

Gil de los Santos, D., Gil Turnes, C. and Rochedo Conceição, F. 2012. Bioremediation of parboiled rice effluent supplemented with biodiesel-derived glycerol using *Pichia pastoris* X-33. Sci. World J., 2: 1-5.

Giri, D.R., Singh, E. and Satyanarayan, S. 2016. Comparative study on toxicity evaluation of anaerobically treated parboiled rice manufacturing wastewater through fish bioassay. Water Sci Technol., 73(8): 1825-1831.

Gude, V.G. 2016. Wastewater treatment in microbial fuel cells e an overview. J. Clean. Prod., 122: 287-307.

He, C., Mu, Z., Yang, H., Wang, Y., Mu, Y. and Yu, H. 2015. Electron acceptors for energy generation in microbial fuel cells fed with wastewaters: A mini-review. Chemosphere, 140: 12-17.

Heinemann, R.J.B., Fagundes, P.L., Pinto, E.A., Penteado, M.V.C. and Lanfer-Marquez, U.M. 2005. Comparative study of the nutrient composition of commercial brown, parboiled, and milled rice from Brazil. J. Food Comp. Anal., 18: 287-296.

Hettiarachchy, N.S., Ju, Z.Y., Siebenmorgen, T. and Sharp, R.N. 2000. Rice: Production, Processing, and Utilization. Handbook Cereal Sci. Technology, 203-221.

Hongyang, S., Yalei, Z., Chunmin, Z., Xuefei, Z. and Jinpeng, L. 2011. Cultivation of *Chlorella pyrenoidosa* in soybean processing wastewater. Bioresour Technol., 102(21): 9.

Johansen, M.N. (ed). 2012. Microalgae: Biotechnology, Microbiology, and Energy. Nova Science, New York.

Karichappan, T., Venkatachalam, S., Jeganathan, P. M. and Sengodan, K. 2013. Treatment of rice mill wastewater using continuous electrocoagulation technique: optimization and modeling. J. Korean Chem. Soc., 57(6): 761-768.

Karul, C., Soyupak, S., Çilesiz, A.F., Akbay, N. and Germen, E. 2000. Case studies on the use of neural networks in eutrophication modeling. Ecol. Model., 134(2-3): 145-152.

Karunaratne, H.W.G.I. and Gunasekera, M.Y. 2010. Removal of Pollutants In Soak Water Resulting from Parboiling of Paddy. M. Tech. Thesis. Department of Chemical and Process Engineering of the University of Moratua, Sri Lanka.

Kato, H., Ohta, T., Tsugita, T. and Hosaka, Y. 1983. Effect of parboiling on texture and flavor components of cooked rice. J. Agri. Food Chem., 31(4): 818-823.

Keerthana, S., Sekar, S., Kumar, S.D., Santhanam, P., Divya, M., Krishnaveni, N., Arthikha R. and Kim, M.K. 2020. *Scenedesmus pecsensis* cultivation in rice mill effluent using commercial scale nutrient sources. Bioresour. Technol. Rep., 9: 100379.

Kim, J., Lingaraju, B.P., Rheaume, R., Lee, J. and Siddiqui, K.F. 2010. Removal of ammonia from wastewater effluent by *Chlorella vulgaris*. Tsinghua Sci. Technol., 15(4): 391-396.

Kumar, A., Priyadarshinee, R., Roy, A., Dasgupta, D. and Mandal, T. 2016. Current techniques in rice mill effluent treatment: emerging opportunities for waste reuse and waste-to-energy conversion. Chemosphere, 164: 404-412.

Kumar, A., Singha, S., Dasgupta, D., Datta, S. and Mandal, T. 2015. Simultaneous recovery of silica and treatment of rice mill wastewater using rice husk ash: An economic approach. Ecol. Eng., 84: 29-37.

Kumar, S. and Deswal, S. 2020. Phytoremediation capabilities of Salvinia molesta, water hyacinth, water lettuce, and duckweed to reduce phosphorus in rice mill wastewater. Int. J. Phytoremed., 22(11): 1097-1109.

Laliberte, G., Lessard, P., De La Noüe, J. and Sylvestre, S. 1997. Effect of phosphorus addition on nutrient removal from wastewater with the Cyanobacterium *Phormidium bohneri*. Bioresour. Technol., 59(2-3): 227-233.

Lopes, L.F., Koetz, P.R. and Santos, M.S. 2001. Denitrification on the top of UASB reactors of rice wastewater. Water Sci. Technol., 44(4): 79-82.

Manogari, R., Daniel, D. and Krastanov, A. 2008. Biodegradation of rice mill effluent by immobilized *Pseudomonas* sp. cells. Ecol. Eng. Environ. Protect., 1: 30-35.

Mishra, S., Mohanty, M., Pradhan, C., Patra, H.K., Das, R. and Sahoo, S. 2013. Physicochemical assessment of paper mill effluent and its heavy metal remediation using aquatic macrophytes - A case study at JK Paper mill, Rayagada, India. Environ. Monit. Assess., 185(5): 4347-4359.

Mukherjee, B., Majumdar, M., Gangopadhyay, A., Chakraborty, S. and Chatterjee, D. 2015. Phytoremediation of parboiled rice mill wastewater using water lettuce (Pistia Stratiotes). Int. J. Phytoremed., 17(7): 651-656.

Obayashi, A.W. and Gaudy Jr., A.F. 1973. Aerobic digestion of extracellular microbial polysaccharides. J. Water Pollut. Contr. Fed., 174: 1584-1594.

Oli, P., Ward, R., Adhikari, B. and Torley, P. 2014. Parboiled rice: understanding from a materials science approach. J. Food Eng. 124: 173-183.

Oswald, W.J., Gotaas, H.B., Golueke, C.G., Kellen, W.R., Gloyna, E.F. and Hermann, E.R. 1957. Algae in waste treatment (with discussion). Sewage Ind. Waste, 29(4): 437-457.

Pani, S.C. 1986. Aspects of Ecological Studies on Tropical Earthworms in the Irrigated Agricultural System of Orissa, India. Ph.D. Thesis, Sambalpur University, p. 232.

Pant, D., Van Bogaert, G., Diels, L. and Vanbroekhoven, K. 2010. A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. Bioresour. Technol., 101: 1533-1543.

Pathak, V.V., Singh, D.P., Kothari R. and Chopra, A.K. 2014. Phycoremediation of textile wastewater by unicellular microalga *Chlorella pyrenoidosa*. Cell. Mol. Biol., 60(5): 35-40.

Paul, J., Abhijith, D., Vr, A.R., Joy, J. and Latheef, S. 2015. Environmental impact of rice mills on groundwater and surface water. Int. J. Civ. Struct. Eng. Res., 3(1): 11-15.

Pavlineri, N., Skoulikidis, N.T. and Tsihrintzis, V.A. 2017. Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. Chem. Eng. J., 308: 1120-1132.

Peixoto, G., Pantoja-Filho, J.L.R., Agnelli, J.A.B., Barboza, M. and Zaiat, M. 2012. Hydrogen and methane production, energy recovery, and organic matter removal from effluents in a two-stage fermentative process. Appl. Biochem. Biotechnol., 168(3): 651-671.

Pradhan, A. and Sahu, S.K. 2004. Process details and effluent characteristics of a rice mill in the Sambalpur district of Orissa. I Contr. Pollut., 20(1): 414-436.

Pradhan, A. and Sahu, S.K. 2011. Effect of rice mill wastewater on population, biomass, rate of reproduction, and secondary production of *Drawida willsi* (Oligochaeta) in rice field agroecosystem. Int. J. Res. Rev. Appl. Sci., 6(2): 138-146.

Queiroz, M.I., Lopes, E.J., Zepka, L.Q., Bastos, R.G. and Goldbeck, R. 2007. The kinetics of the removal of nitrogen and organic matter from parboiled rice effluent by cyanobacteria in a stirred batch reactor. Bioresour. Technol., 98(11): 2163-2169.

Rajesh, G., Bandyopadhyay, M. and Das, D. 1999. Some studies on UASB bioreactors for the stabilization of low-strength industrial effluents. Bioprocess Eng., 21(2): 113-116.

Rambabu, K., Bharath, G., Thanigaivelan, A., Das, D.B., Show, P.L. and Banat, F. 2021. Augmented biohydrogen production from rice mill wastewater through nano-metal oxides assisted dark fermentation. Bioresour. Technol., 319: 124243.

Rambabu, K., Show, P.L., Bharath, G., Banat, F., Naushad, M. and Chang, J.S. 2019. Enhanced biohydrogen production from date seeds by *Clostridium thermocellum* ATCC 27405. Int. J. Hydrog. Energy, 45: 22271-22280.

Ramprakash, B. and Muthukumar, K. 2014. Comparative study on the production of biohydrogen from rice mill wastewater. Int. J. Hydrog. Energy, 39(27): 14613-14621.

Ramprakash, B. and Muthukumar, K. 2015. Comparative study on the performance of various pretreatment and hydrolysis methods for the production of biohydrogen using *Enterobacter aerogenes* RM 08 from rice mill wastewater. Int. J. Hydrog. Energy, 40(30): 9106-9112.

Ramprakash, B. and Muthukumar, K. 2016. Biohydrogen production from rice mill wastewater using mutated *Enterobacter aerogenes*. Eng. Agric. Environ. Food, 9(1): 109-115.

Ramprakash, B. and Muthukumar, K. 2018. Influence of sulfuric acid concentration on biohydrogen production from rice mill wastewater using pure and coculture of *Enterobacter aerogenes* and *Citrobacter freundii*. Int. J. Hydro. Energy, 43(19): 9254-9258.

Ramprakash, B., Lindblad, P., Eaton-Rye, J.J. and Incharoensakdi, A. 2022. Current strategies and future perspectives in biological hydrogen production: A review. Renew. Sustain. Energy Rev., 168: 112773.

Raychaudhuri, A. and Behera, M. 2020. Comparative evaluation of methanogenesis suppression methods in microbial fuel cell during rice mill wastewater treatment. Environ. Technol. Innov., 17: 100509.

Raychaudhuri, A. and Behera, M. 2021. Enhancement of bioelectricity generation by integrating acidogenic compartment into a dual-chambered microbial fuel cell during rice mill wastewater treatment. Process Biochem., 105: 19-26.

Raychaudhuri, A. and Behera, M. 2022. Effect of operating parameters on rice mill wastewater treatment in an acidogenic chamber and MFC coupled system. Bioresour. Technol. Rep., 10: 249.

Raychaudhuri, A., Sahoo, R.N. and Behera, M. 2022. Sequential anaerobic-aerobic treatment of rice mill wastewater and simultaneous power generation in the microbial fuel cell. Environ. Technol., 16: 1-7.

Reddy, S.S.G., Raju, A.J.S. and Kumar, B.M. 2015. Phytoremediation of sugar industrial water effluent using various hydrophytes. Int. J. Environ. Sci., 5(6): 1147.

Sadhasivam, S. and Jayanthi, S. 2021. An experimental study on biogas production by anaerobic digestion of rice mill wastewater. Glob. NEST J., 23(1): 27-34.

Saha, P., Shinde, O. and Sarkar, S. 2017. Phytoremediation of industrial mines wastewater using water hyacinth. Int. J. Phytoremed., 19(1): 87-96.

Saini, J.K., Saini, A. and Lohchab, R.K. 2016. Rice mill wastewater treatment by up-flow anaerobic sludge blanket reactor. Int. J. Plant Anim. Environ. Sci., 6(3): 128-134.

Singh, D., Gupta, R. and Tiwari, A. 2012. Potential of Duckweed (Lemna minor) for removal of lead from wastewater by phytoremediation. J. Pharm. Res., 5(3):1578-1582.

Solovchenko, A., Pogosyan, S., Chivkunova, O., Selyakh, I., Semenova, L., Voronova, E. and Lobakova, E. 2014. Phyco-remediation of alcohol distillery wastewater with a novel *Chlorella sorokiniana* strain cultivated in a photobioreactor monitored online via chlorophyll fluorescence. Algal Res., 6: 234-241.

Statistica 2021. Production volume of rice in India FY 2010-2022- Statistica. https://www.statistica.com>statistics

Tomlins, K.I., Manful, J.T., Larwer, P. and Hammond, L. 2005. Urban consumer preferences and sensory evaluation of locally produced and imported rice in West Africa. Food. Qual. Pref., 16 (1): 79-89.

Umamaheswari, J. and Shanthakumar, S. 2020. Optimization of temperature and inoculum size for phyco-remediation of paddy-soaked rice mill wastewater. J. Environ. Eng., 146(1): 04019091.

Unnikrishnan, K.R. and Bhattacharya, K.R. 1987. Influence of varietal difference on properties of parboiled rice. Cereal Chem., 65(4): 315-321.

USEPA 2022. Global Greenhouse Gas Emission Data. US Environmental Protection Agency

Varshney, C.K. 2012. All India Rice Exporters Association Event. Available online at: http://www.airea.net/Events-Rice (Accessed on 17.12.2021).

Wang, H., Xiong, H., Hui, Z. and X. Zeng. 2012. Mixotrophic cultivation of *Chlorella pyrenoidosa* with diluted primary piggery wastewater to produce lipids. Bioresour. Technol., 104: 215–220.

Wang, W., Xie, L., Chen, J., Luo, G. and Zhou, Q. 2011. Biohydrogen and methane production by co-digestion of cassava stillage and excess sludge under thermophilic conditions. Bioresour. Technol., 102: 3833-3839.

Whitton, B.A. and Potts, M. 2012. Introduction to the Cyanobacteria. Ecology of Cyanobacteria II: Their Diversity in Space and Time. Springer, NY, 1-13.