LEMNACEAE *BIOMASS* AS AN ALTERNATIVE SUBSTRATE FOR RENEWABLE ENERGY

Zdzisława Romanowska-Duda, Wiktor Pszczółkowski
University of Łódź, Faculty of Biology and Environmental Protection
ul. Pomorska 141/143, 90-001 Łódź, romano@biol.uni.lodz.pl, wiktorpszczolkowski@gmail.com

Abstract
This article describes the possibilities of using Lemnaceae biomass as a possible raw material for the development of renewable energy. In the first part, the authors analyze the causes of eutrophication as a process of enrichment of water reservoirs that favors the development of potential energy substrates. Next, the role of macrophytes in restoring the ecological balance of freshwater ecosystems, as well as the biofuel potential of *Lemnaceae* plants, is presented.

Key words
Lemnaceae biomass, renewable energy sources, biofuel eutrophication

Introduction: Eutrophication and its causes

Eutrophication of water reservoirs, most often resulting from anthropopression, is becoming an increasingly common phenomenon. The cause of this process is an increase in the inflow of nutrient basins, mainly nitrogen (N) and phosphorus (P), and excessive waste of lakes and rivers with sewage containing powerful amounts of phosphates from detergents. Excessive emissions of nitrogen oxides into the atmosphere result in increasing amounts of nitrogen, along with precipitation, in large water bodies. In addition, incorrect fertilization of fields and improper plowing contribute to the elimination of significant quantities of this element from the surface layers of the soil. The participation of wind erosion is also noteworthy, mainly in dry areas, where wind can easily pick up soil particles with biogenic substances and transfer them to the reservoir. In addition, because of the melioration and liquidation of retention reservoirs (marshy areas and small water bodies), the organic matter is mineralized.

In the first stage of eutrophication, there is a slight increase in biological production and a growing population of fish, which is a positive factor from the point of view of fisheries. Later stages include phytoplankton blooms in which particularly toxic cyanobacteria grow. They reduce water transparency, release harmful toxins, negatively affect the taste and odor of water and reduce oxygen levels, resulting in massive fish die-off.

Cyanobacteria blooms are not only aesthetically problematic, but are primarily hazardous to health as they can produce hepato- and neurotoxins [1-13], causing disease or lethal poisoning [14-17]. Studies [18, 19] describe cases of cytotoxic and genotoxic effects caused by cyanotic toxins.

In the litoral zone, inadequate lighting conditions contribute to the disappearance of submerged vegetation. This is due to the increase in the level of biogenic elements that favor the intensive development of phytoplankton, which covers the surface of the submerged plants. As a result, macrophytes are displaced by filamentous forms of phytoplankton (*Cladophora, Spirogyra*). Bottom sediments and hypolymnion are deoxygenated. In such an environment, oxalic organisms have no chance of development and many species of pelagic fish cannot reproduce. Anaerobic conditions favor the occurrence of processes such as desulfurization, denitrification, ammonification or finally the formation of methane and hydrogen sulphide. Because of these phenomena, the internal fertilization of the lake is started, which further intensifies the eutrophication process.

Phosphorus, in addition to nitrogen and carbon, is generally considered to be the main determinant of trophic levels of water bodies. As with all biogenic substances, phosphorus compounds reach the lake from the catchment by surface and ground flow, both from sewage and from the atmosphere [20-22]. This element from external sources reaches the reservoirs in the form of mineral and organic compounds dissolved and suspended in water. Mineral phosphates are directly available for algae and plants, while phosphorus esters and organic phosphorus compounds are hydrolysed by phosphohydrolase enzymes (acidic and alkaline phosphatases) or are lysed into the form of assimilable orthophosphate [23-26].

The role of macrophytes in restoring the ecological balance of freshwater ecosystems

Water *macrophobia*, including floating *Lemnaceae*, play a significant role in regulating nutrient dynamics in freshwater ecosystems. Significant biomass of these plants can act as a buffer against eutrophication [27], stabilize ecological processes and biogenic circulation in aquatic ecosystems, and enable the reproduction of fish [28, 29].

Macrophytes are a tool for sustainable development in freshwater ecosystems and should be considered in two complementary areas: low- and medium-level wastewater neutralization technologies and ecohydrology [30-33] as an integrated water management strategy and a tool to increase the ability of freshwater ecosystems to absorb anthropogenic factors. An effective way in the reduction of excessive amounts of phosphorus and nitrogen (Tab. 1) is a natural or artificial introduction of macrophytes into the reservoir and additional biomanipulatory techniques leading to improved water transparency, and then at a later stage to obtain the state of clean water [34, 35].

Tab. 1. Daily intake of nitrogen and phosphorus by duckweed (according to Floating aquatic macrophytes – duckweeds - *FAO* 1997)

Country	Plant species	Collecting in g/m^2	
		N	P
Italy	*L. gibba*, L. *minor*	0.42	0.01
Czech Republic	duckweed	0.20	-
USA	*Lemna* sp.	1.67	0.22
USA/Louisiana	duckweed	0.47	0.16
India	*Lemna* sp.	0.50-0.59	0.14-0.30
USA/Minnesota	*Lemna* sp.	0.27	0.04
USA/Floryda	*S. polyrrhiza*	-	0.015

Macrophytes affect:

- the accumulation of elements in the tissues leading to a reduction of the orthophosphate pool;
- the allelopathic effect, inhibiting the development of phytoplankton [36-39];
- the oxidation of bottom sediments and reduction of phosphorus release from sediments [40];
- reduced turbidity of water due to restriction of rippling and resuspension of sediments;
- the presence of invertebrate with significant condensation of macrophytes [35].

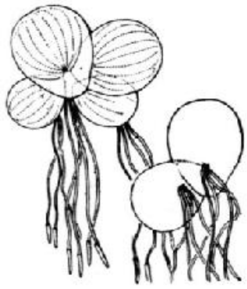
The relationships between macrophytes and abiotic ecosystem components and other biotic representatives are multidimensional and express unique patterns of interactions for different climates and typologically diverse ecosystems [33].

Understanding the physiology and reaction of individual plant species, including the *Lemnaceae* family, is essential for the optimum use of phytotechnology in a given environment.

Characteristics of plants from the *Lemnaceae* family

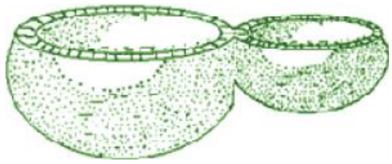
Plants belonging to the *Lemnaceae* family are very small, leafless, have small green flattened shoots slowly floating on the surface of waters (nymphs) or submerged under water (elodeids). Only *Wolfia* floats freely in water. *Lemnaceae* develop one root or a bunch of roots on the lower surface. They can also sometimes be without roots. Flowers are very rare and single sex. These plants cover the surface of stagnant water and serve as food for water birds, fish, domestic birds, and farm animals [41].

Representatives of the *Lemnaceae* (*cilia*) family belong to five types:



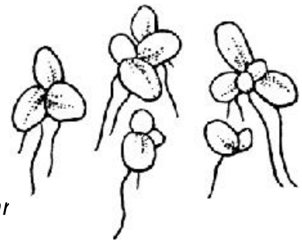
Landolti

Wolfia



Wolfiella

Lemr



These plants are a very popular source of organic matter. Tab. 2 presents the classification of selected plant species of the *Lemnaceae* family.

Tab. 2. Selected species from the *Lemnaceae* family (according to Floating aquatic macrophytes – duckweeds - *FAO* 1997)

Lemna	**Spirodela**	**Wolffia**	**Wolffiella**
L. gibba	*S. biperforata*	*W. arrhiza*	*W. caudate*
L. disperma	*S. intermedia*	*W. australiana*	*W. denticulata*
L. japonica	*S. oligorrhiza*	*W. columbiana*	*W. lingulata*
L. minima	*S. polyrrhiza*	*W. microscopia*	*W. oblinga*
L. minor	*S. punctate*	*W. neglecta*	*W. rotunda*
L. minuscula			
L. paucicostata			
L. perpusilla			
L. polyrrhiza			
L. turionifera			
L. trisulca			
L. valdiviana			

In Poland, common species are lesser duckweed (*Lemna minor*), ivy-leaved duckweed (*Lemna trisulca*), gibbous duckweed (*Lemna gibba*), *Spirodela polyrrhiza* and rootless duckweed (*Wolffia arrhiza*).

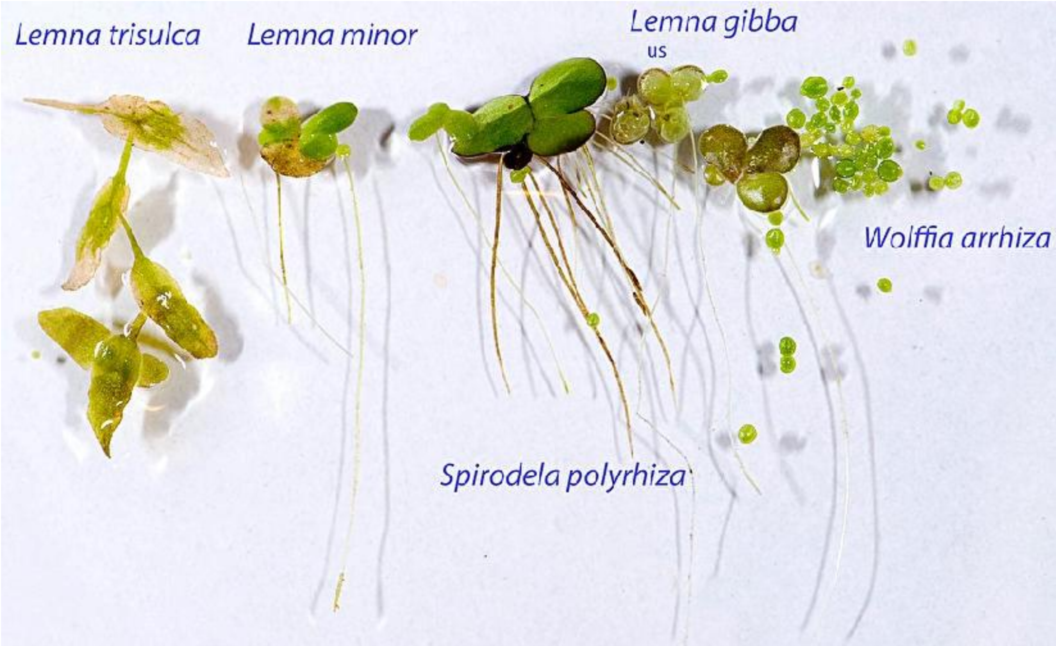


Fig. 1. Comparison of national representatives of the duckweed family (*Lemnaceae*)
Source: [42]

Water plants from the *Lemnaceae* family have many advantages compared to typical energy crops. They are characterized by a higher biomass growth rate, which can double after 24 hours, and their natural environment is inland water reservoirs. As a result, they are not competition for soil cultivation, especially for food or feed purposes. There are reports on the use of this kind of aquatic biomass as a substitute for renewable energy production, and at present this group of plants is also seen as a high-value raw material in biogas production, bioethanol production, biodiesel, animal feed and in phytoremediation processes of contaminated inland waters.

Aquatic biomass of *Lemnaceae* plants

At present, one of the most important and most widely developed directions in the production of renewable energy is the use of biomass, including water plants. Research on the production of biofuels like bioethanol and biodiesel from aquatic biomass has become dynamic, due to the possibility of becoming independent of fossil fuels and reducing CO_2 emissions.

In the production of traditional energy crops, many problems can arise related to the competitiveness of available soils and their intended use for consumption, the reduction of biodiversity of energy crops, and the consumption of very large quantities of water. Water is a highly valuable natural resource whose value is constantly increasing due to progressive environmental pollution. Therefore, it is important to properly clean and reuse water resources.

Another problem is fertilization and the use of pesticides in energy crops. That is why new and energy-efficient biomass sources of plants are being sought, whose production will be pro-ecological. The combination of *Lemnaceae* biomass production with the treatment of industrial effluents and wastes is a sustainable form of biofuel production with respect to water purity and waste recycling [43]. A promising energy potential can be the use of water plants from the *Lemnaceae* family. Plants from the *Lemnaceae* family have been well-researched for their use in phytoremediation of both organic and inorganic pollutants and have many beneficial features. They are characterized by rapid growth and high primary production, high bioaccumulative potential, biotransformation, and biodegradation. They also control the spread and bioavailability of some contaminants.

Particularly noteworthy is the ability to accumulate heavy metals, radionuclides, and trace elements at a higher rate than other water plants or algae. For many of these elements, *Lemna* species are hyperaccumulators; they accumulate more than 1,000 mg of elemental matter per kilogram of dry matter. In addition, *Lemnaceae* plants tolerate high concentrations of various contaminants occurring simultaneously. They also produce and release into the environment low molecular weight organic compounds that increase the bioavailability and bioaccumulation of pollutants. Their high efficiency in removing elements such as nitrogen, phosphorus, potassium, calcium, magnesium, sodium, and iron has been proven. The use of *Lemna* sp. for biological wastewater treatment resulted in a reduction in COD (chemical oxygen demand) and BOD (biological oxygen demand) and an 88% reduction in ammonia content. In addition, the presence of *Lemnaceae* reduced evaporation by 20% compared to open wastewater treatment systems.

Lemnaceae can be used as a raw material for efficient and economically viable bioethanol production due to its very high starch accumulation (up to 70% dry matter) and low cellulose content (about 10%). The method of growing *Spirodella polyrrhiza* and conversion of its biomass to bioethanol is presented in [44]. *Lemna minor* is also potentially a viable raw material for bioethanol production. Compared to land plants, there is little lignin and hemicellulose, which, at the current technological level, cannot be effectively used to produce large-scale biofuels. Both the starch and cellulose fractions contained in *Lemna minor* biomass are susceptible to enzymatic degradation to glucose without the need for pre-treatment of heat. In addition, such enzymatic hydrolysis improves ethanol fermentation efficiency [45]. Production of biomass of *Lemnaceae* can occur in bioreactors or open tanks. *Lemnaceae* ponds have been recognized as an effective and inexpensive method for the final treatment of agricultural wastes such as slurry. This system has shown one of the highest levels of nitrogen removal, with a high growth rate of high protein biomass.

Tab. 3. Chemical composition (% dry matter)

Parameter/Plant	Lucerne	Corn silage	*Lemnaceae*
Organic matter	89.3	94.7	78.5
Proteins	19.2	6.25	23.0
Natural fibers	37.0	42.2	30.2
Sour fiber	27.4	22.7	13.7
Humidity	75-83	60-70	92-94

Such biomass can potentially be used as feed for pigs. Due to the high content of lysine and methionine, the protein contained is more that from animals than from vegetables [46]. The production of *Lemnaceae* in prepurified slurry significantly reduced the negative impact on the environment, and the use of biomass as feed could potentially improve crop yield [47]. Numerous studies have shown the efficacy of *Lemnaceae* for the treatment of urban and agricultural waste, and the multidirectional use of biomass produced including biogas, biofuels, bioremediation, phytoremediation, and high protein fodder (Fig. 1).

The European Biofuels Technology Platform promotes the concept of biorefineries as a producer of many valuable products and is a comprehensive technology system that combines the processes of biomass conversion and further processing of its products. These products should be environmentally friendly and not pose a threat to the environment, especially in terms of greenhouse gas emissions. These tasks fit perfectly within the scope of research of the Polish Technology Platform for Biofuels and Biocomponents for national assumptions, including the introduction of new plant varieties to produce biofuels [48, 49].

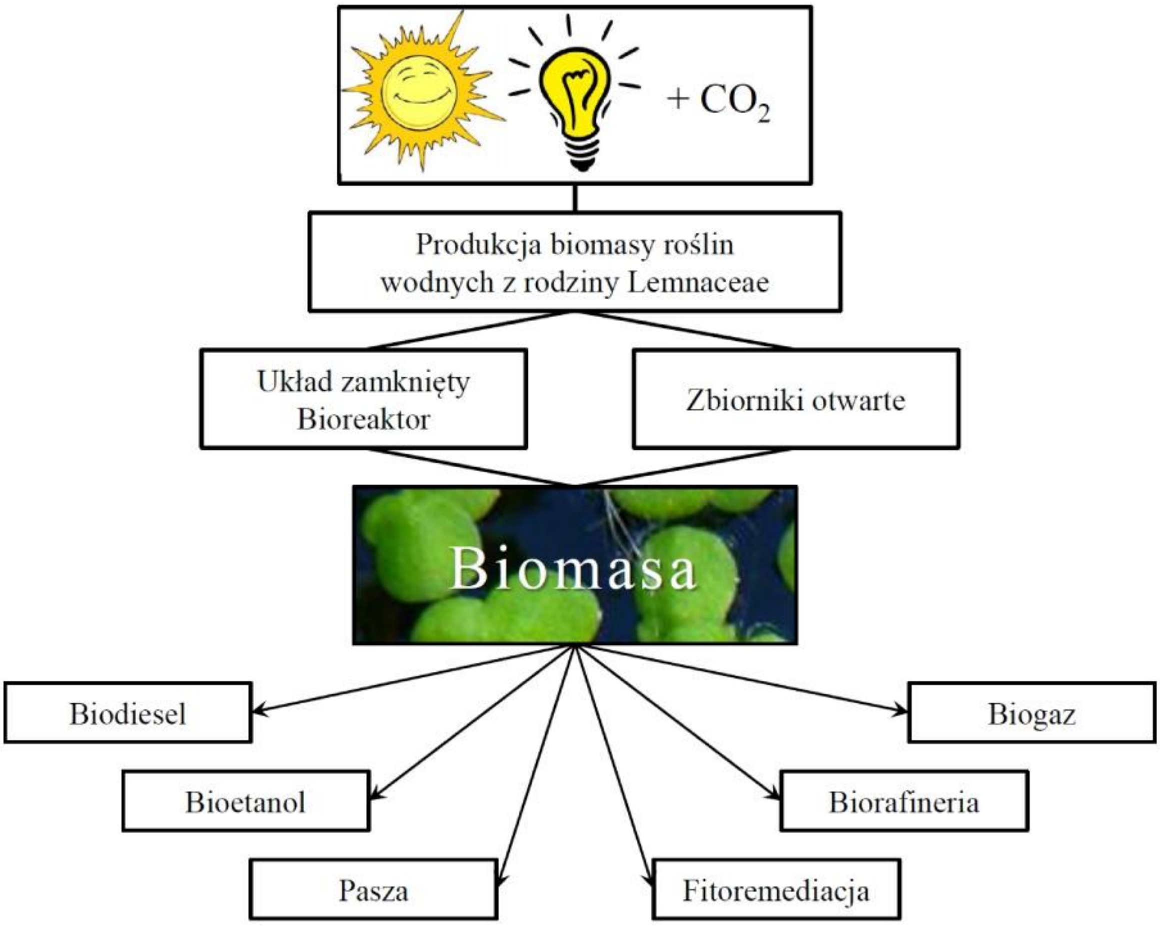


Fig. 1. Scheme of use of plants from the Lemnaceae family
Source: own study

The problem of the disposal of dairy waste includes the development of innovative energy technologies based on the production of new aquatic biomass resources of *Lemnaceae*, which can be successfully available in rural areas and do not interfere with the food production functions of agriculture. The cultivation of *Lemnaceae* water plants using wastewater and liquid organic waste from the dairy industry as well as biogas production will produce plant biomass of various applications, including phytoremediation of water bodies. This method is an effective way of managing waste from the dairy industry and an economical high-quality biomass production system with a wide range of applications in bioenergy (liquid and gaseous biofuels) and agriculture (feed, fertilizer). The dynamic development of biogas plants facilitates the search for cheap and available plant biomass, including *Lemnaceae*, and leads to the sustainable development of the environment.

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