Allelopathic Potential of *Lemna minor* L.

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Allelopathy is an interaction that releases allelochemicals (chemicals that act allelopathically) from plants into the environment that can limit or stimulate the development, reproduction, and survival of target organisms and alter the environment. *Lemna minor* L. contains chemicals that are allelopathic, such as phenolic acids. Chemical compounds contained in *L. minor* may have a significant impact on the development and the rate of multiplication and lead to stronger competition, which may enhance the allelopathic potential. Allelopathic potential may exist between *L. minor* and *C. glomerata* (L) Kütz. because they occupy a similar space in the aquatic ecosystem, have a similar preference for the amount of light, and compete for similar habitat resources. *L. minor* and *C. glomerata* can form dense populations on the water surface. Allelopathy can be seen as a wish to dominate one of the plants in the aquatic ecosystem. By creating a place for the development of extensive mats, an interspecific interaction is created and one of the species achieves competitive success. It is most effective as a result of the release of chemicals by macrophytes into the aquatic environment. Therefore, allelopathy plays a significant role in the formation, stabilization, and dynamics of the structure of plant communities.

Keywords: duckweed ; pleustophytes ; macroalgae ; allelopathy ; competition ; polyphenols

1. Allelopathic Potential of Lemna minor *L.*

Allelopathy can have a variety of practical applications in both terrestrial and aquatic environments. However, it is most commonly used in agriculture, e.g., to remove weeds, diseases, and microorganisms that are harmful to crops, as well as to improve the condition of crops and to effectively increase their yields [1][2][3]. Allelopathy is probably one of the most modern and effective methods for agriculture. In turn, allelopathic substances act in a similar way to herbicides, being an effective tool for controlling weeds in plant crops [4]. According to research, *Lemna minor* L. contains chemicals that are allelopathic [5][6]. Previous studies have confirmed that aqueous methanol extracts isolated from *L. minor* have a significant effect on monocotyledons (cress, lettuce, and alfalfa) and dicotyledons (rye grass, timothy, barnyard grass, crab grass, and junglerice) [1]. Small amounts of methanol extract (0.1 g DW eq. extract mL^{-1}) limit the growth of shoots and roots in cress, lettuce, and rye grass, as well as timothy and crab grass roots [1]. At a higher concentration (1 g DW eq. extract mL^{-1}), the development of shoots and roots in barnyard grass, junglerice, crab grass, and rye grass is inhibited [1]. Among the plants studied, methanol extract most strongly inhibited the development of alfalfa shoots and timothy roots [1]. Subsequent studies have shown that substances present in *L. minor*, such as flavonoids and fatty acids, have an inhibitory effect on the growth of walnut biomass [1]. As reported in the literature, plant extracts are also bacteriostatic in nature, which has been demonstrated in *Sphaerotilus natans* [3]. In *L. minor*, there are substances with antioxidant and anti-radical properties and pharmacological properties, such as phytol; campesterol; loliolide; dihydroactinediol; ascorbic acid; vanillic acid; 2,3-dihydroxybenzoic acid; caffeic acid; chlorogenic acid; esculetin; esculin; and fraxetin [6][7][8]. A characteristic feature of *L. minor* is its simple morphology, rapid biomass growth rate, and high sensitivity to changes in the ecosystem. As a result, it is often used in toxicological studies of the environment [4][5][9]. Because of its high protein content, *Lemna minor* is used in agriculture as an effective biopesticide [1][2][9]. It eliminates phenolic compounds from the aquatic environment, which arise as a result of industrial development and are toxic to organisms [9][10]. This confirms the bioremediation abilities of *L. minor* [10]. Bioremediation consists in improving the ecological condition of the environment with the use of organisms and their ability to remove or reduce the concentration of harmful pollutants. Due to the fact that *L. minor* is resistant to oxidative stress and the accumulation of reactive oxygen species (ROS), which are the result of the presence of phenolic compounds in the environment, it may contribute to the improvement of water quality [9][11]. The ability to produce biomass quickly can be used to treat wastewater with a high content of organic compounds or heavy metals. *L. minor* has a high tolerance to water contaminated with metals [12]. It is a good hyperaccumulator of lead, nickel, chromium, copper, cadmium, and manganese [12]. This plant is also highly effective in removing arsenic, Ni, Zn, Fe, and Cd from aquatic ecosystems [12]. So far, little research has been carried out to confirm the allelopathic potential of *Lemna minor* or to explain the mechanism of this phenomenon. Nevertheless, the use of this plant as a tool for managing the aquatic and terrestrial environment seems to be an extremely important solution for polluted ecosystems.

2. Models of Lemna minor *L.* and Cladophora glomerata (*L.*) Kütz Population Formation: Interactions between Species

Large amounts of nutrients are present in eutrophic water bodies. The consequence of this is the excessive development of biological life, including the massive appearance of phytoplankton organisms and other aquatic plants that create blooms on the water surface and reduce the transparency of the water. An excessive development of green algae, mainly *Cladophora* (Chlorophyta) species, is observed in eutrophic water reservoirs. *Lemna minor*, belonging to the Lemnaceae family, is also a common aquatic plant.

Lemna minor is a small plant (pleustophyte) with a simple morphological structure. It consists of a single thallus and has no root [13][14]. The plant reproduces mainly vegetatively [15]. In summer, *L. minor* forms single-species, dense, and compact clusters that float freely on the water surface [5][16]. These patches inhibit the development of other macrophytes, limiting their access to light by up to 99% [17]. The increase in plant biomass over a short time contributes to the eutrophication of the aquatic ecosystem. To survive the colder months, the pleustophyte forms small turions that are filled with starch and sink to the bottom of the water reservoir [6][18]. Most often, *L. minor* occurs in waters with a temperature of 6 to 33 °C. It also has a wide range of pH tolerance, from 5 to 9 [19]. *L. minor* prefers shallow places with low water turbulence that are rich in electrolytes [17][20]. The growth, survival rate, and growth rate are influenced by various ecological factors, e.g., pH, water temperature, concentration of nutrients, presence and concentration of toxins in water, as well as competition with other plants for light and nutrients [18]. However, temperature and light availability are the factors that best stimulate the proper growth and development of *L. minor* [18]. It has the ability to absorb minerals as well as phosphorus and potassium that are present in nutrient-rich water [18]. A threat to the development of *L. minor* is the intense growth of algae, including the green algae of the genus *Cladophora*, which limit the plant's access to light and nutrients [18]. As a result, it has limited space and resources to create dense colonies on the surface of a body of water.

Cladophora glomerata (L) Kütz. is a green alga that dominates in eutrophic waters [21][22]. Due to the diversified morphology of the plant, the thallus may be long and branched in flowing waters and short and bushy in stagnant waters [23]. The lifting force of water enables the movement of the thallus, which can change its shape and place of occurrence. It creates filamentous forms, called grippers, by means of which it attaches to the ground or floats in the water column [23]. *C. glomerata* forms dense and large populations ("mats") on the surface of a water body [17][24]. Intensive development occurs in spring and autumn, as a result of which it creates massive blooms [23]. The density and size of the biomass often depend on the growing season and the environmental conditions in which it grows [25]. Green alga mats may consist of individuals of one species (*Cladophora glomerata*) or of several co-occurring species [21]. Although *C. glomerata* occurs in most types of aquatic ecosystems (from stagnant waters to flowing waters), it is most numerous in eutrophic waters with a high concentration of nitrogen and phosphorus [17][21]. It has preference for a wide range of temperatures and light conditions; therefore, it easily adapts to the ecosystem it currently inhabits [17][21]. Owing to its uncomplicated morphological structure, rapid multiplication rate, and high ecological tolerance, *C. glomerata* easily forms large populations and occupies considerable space [22][25]. This alga can limit access to light by up to 70%, create anaerobic conditions, and inhibit the supply of nutrients and thus inhibit the development of macrophytes [22][25][26]. *C. glomerata*, similarly to *L. minor*, prefers waters with a high content of nutrients as well as nitrogen and phosphorus [25]. An important element for the proper growth of green algae is the optimal chemical composition of water, in which there is a high concentration of nitrates and orthophosphates [21].

As shown in the above literature data, *L. minor* and *C. glomerata* are species with similar ecological preferences. Both plants occupy a similar space in the aquatic ecosystem, have a similar preference for the amount of light, and compete for similar habitat resources. Both *L. minor* and *C. glomerata* can form dense populations that float on the water surface. As a result, they inhibit the growth of other hydro macrophytes as they restrict their access to light and nutrients. Their chemical composition indicates the presence of substances with an allelopathic effect. The presence of phenols such as phenyl ester, methoxylphenol, coumaric acid, and benzoic acid has been found in the thalli of filamentous green algae [27]. Unfortunately, there is little research explaining the mechanism of interaction between these plant species.

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