APPLICABILITY OF DUCKWEED TO INCREASE FOOD SECURITY IN AFRICA

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Abstract:

A sizable portion of African soil is regarded as arable. They do, however, have a severe food shortage. The main causes of food insecurity in Africa are war, hostilities, political unrest, inflation, poverty, and environmental disaster. Extreme weather occurrences including protracted droughts and disastrous floods have significantly increased as a result of the climate catastrophe. The unfavorable weather has a negative impact on agriculture and the economy. Destroying the forests to make room for homes and the expanding population puts additional pressure on the green belt. Globally, notably in Africa, the availability of freshwater resources has been severely impacted by the rise in global temperatures. This has had a significant influence on agricultural land, worsening the food deficit for both humans and livestock. The demand for protein-rich food has increased greatly in Africa, to tackle malnutrition on large scale. The dependence on animal-derived proteins further degrades the environment and has a wide carbon-foot print. The unsustainable and irritational agricultural practices, further aggravate food insecurity in Africa. Thus, it is now more important than ever to use eco-friendly and sustainable methods to increase food production in Africa. Strong resistance against unfavorable climatic circumstances and adaptability to a wide range of environmental factors are essential for the optimum food production system. The paper examines one such option - duckweeds, which have the potential to not only be a useful food source but also to purify wastewater so that it can be used as a supply of freshwater. These aquatic plants are the most attractive choices for animal feed because of their great nutritional content. Due to their high vitamin, mineral, and antioxidant content as well as post-harvest processing, duckweed may be suitable for human consumption and provide a number of health benefits. Duckweeds have a great deal of bioaccumulation potential and are the most useful and economical biological entities for treating wastewater with the goal of water recycling and conservation, which could aptly mitigate the negative effects of water scarcity in Africa.

Keywords:* *Food insecurity, Sub-Saharan Africa, Malnutrition, Duckweeds, Wastewater treatment, Tailwater.

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1 Introduction

The earth has been pushed beyond the point of no return by our activity. The increasing concentration of greenhouse gases in the atmosphere has severely affected the entire biosphere by causing global warming. The global impact of the climate problem cannot be denied. Africa has been entrapped in the grip of climate change and global warming, like many other nations. Numerous African countries' economies, ecology, and water resources are being severely harmed by water stress and the risks of debilitating droughts and destructive floods. Key lakes and glaciers in Africa are significantly shrinking due to altered rainfall patterns and extreme heat.

The stability of many African countries is greatly threatened by the rising demand for drinkable water and the limited unexpected supplies, which can result in conflicts and forced migration. The primary causes of declining human health, food shortages, and obstacles to socioeconomic growth in Africa are extreme weather and climate change. The population of Africa is growing exponentially, but the current agricultural output cannot feed the continent's growing population.

African countries constantly face food insecurity. Food security could be defined as "a condition where all the portions of the population, at all times possess the physical, social and economic access to sufficient and safe food that is as per the dietary needs and food preferences for living a healthy and active life" [1]. Food insecurity occurs when the stated conditions are not met.

It is necessary to investigate a number of sustainable methods and approaches for enhancing food security in Africa. The alternative must be affordable, practical, require the least amount of arable land, and have almost no significant environmental stress.

Growing duckweed to combat food insecurity in Africa is one such solution that has the majority of the advantages and has the potential to be a sustainable food supply.

The tiniest angiosperms, duckweeds, may quickly reproduce and grow with a few less demanding environmental conditions. They are nutrient-dense and could make an excellent substitute for animal-derived proteins in food for both humans and animals.

2 Africa's Current State of Food Availability: Problem Statement

Although Africa possesses more than 60% of the available arable land, the continent is barely able to feed its population with an adequate amount of nutrition. Globally it is ranked second among the numbers of undernourished people. The complexities of the food crisis in Africa are due to several reasons such as corruption and bad governance (not taking action to prevent recurring food shortages), war and conflicts (both internal and external), inflation, poverty, and climate crisis. Many countries in Africa lack self-sufficiency in food crop production as they are net importers of staples like cereals and oils. The net per capita agricultural production in Africa is not sustainable owing to inflation and increased dependence on resources from other continents. Therefore, any political conflict such as the recent one in Ukraine directly impacts the food security in poor nations of Africa.

The food insecurity drivers in each region of Africa vary; therefore, it is perplexing to attenuate the ill effects of hunger and malnutrition throughout the continent with one strategy. For instance, Western, Central, and Southern Africa's food insecurity is mainly impacted by climate shocks including both drought and floods. On another hand, the Northern, Eastern, and Southern African nations have to depend on food subsidies as their farmlands are neither protected from climate shocks nor migratory pests like desert locusts owing to the political instability of these regions [2].

The Horn of Africa (Somalia, Sudan, South Sudan, Ethiopia, Uganda, Kenya, Djibouti) is the most food insecure region of the world [3] as it is badly hit by the compound effects of climate change (drought and floods), conflicts, inflation, and COVID-19 after effects, putting both humans (particularly children) and livestock at risk of perishing. These countries are overly dependent on the import of staple (wheat) from Russia and Ukraine and therefore facing a severe food crisis. Due to the existing and predicted rise in temperatures in the Horn of Africa, the best strategy to tackle food insecurity would be to adopt drought and heat-resistant food crops [3], which require minimum arable land to cease the further degradation of the environment.

One of the global drivers of food insecurity is rapid urbanization which is also observable in African nations such as Nigeria. The continuing flow of populations from rural to urban areas is leading to the conversion of cultivable land to residential areas; thereby negatively affecting agricultural activities [4]. This is a concerning factor across the globe as it leads to loss of farmlands, agricultural productivity, and a steep rise in the domestic water demand and consequently creating huge greywater footprints. As the undue pressure on land and water resources is increasing in Africa and many other regions of the world, the immediate need is to focus on the development of sustainable methods of food production.

The food insecurity arising from lack of food due to lower productivity and higher population growth rate is also increasing the number of malnourished populations, particularly children. The malnourished populations greatly lower the human resource index and put sheer pressure on the health sector as lack of adequate nutrition weakens immunity and thus prone to illness and communicable diseases.

Although climate change seems to be a consequential factor, the prevalence of socio-economic challenges such as high poverty, unemployment. and acute malnutrition (unfit human resources) have far greater impacts on food security in many African countries. The depletion in means of livelihood in countries like Nigeria increases their vulnerability to malnutrition and food insecurity [5]. The three A's viz affordability, availability, and accessibility are key to making investments in the right directions for tackling hunger and nutrition [6]. The three current global barriers namely droughts, biofuels expansion (conversion of agricultural produce to biofuels feedstock), and geo-political trading (leading to a sudden rise in the prices of fuel and food commodities) are high-risk factors for establishing the consistent supply of food chain [6]. Thus, there is a need to introduce non-land-based food sources that are rich in protein and other nutrients such as seaweeds, algae, duckweeds, and sustainable fish farming to tackle food insecurity and malnutrition. The paper goes discusses the details of the duckweed's potential to address the food insecurity that exists in Africa.

3 What Are Duckweeds?

Duckweeds (belonging to *Lemnaceae*) are the tiniest angiosperms, freely floating on the surface of aquatic bodies. Duckweeds are so named as they are efficiently eaten by waterfowls. *Lemnaceae* forms a monocotyledonous family of five genera such as *Spirodela*, *Landoltia*, *Lemna*, *Wolffiella,* and *Wolffia*, encompassing 36 species. Duckweeds possess the simplest body form. The entire body of the duckweed remains in a reduced form as a flat life-like structure, termed as 'fronds' (thallus) (figure 1). These fronds appear to live singly or in groups and may possess one or more capillary roots hanging beneath. The representative members of the three genera (*Spirodela, Landoltia,* and *Lemna*) comprise one or few tiny roots emerging from fronds, while the other two genera are much smaller in size are occurs to be rootless (*Wolffiella* and *Wolffia*) [7]. The fronds usually appear to be bright green. The shapes and sizes of the fronds vary amongst the different genera. For example, in the genus, *Lemna* the shape of fronds appears to be lanceolate to obovate, elliptical, or oblong and 6-8 mm in size [8], while the fronds of *Spirodela* appear to be reniform to obovate with a red underside and 20 mm across. Likewise, the genus *Wolffia* comprises ovoid fronds with 2 mm or less in diameter [8]. However, the lifespan of an individual frond in the vegetative phase seems relatively short – between 3 to 10 weeks [9].

The duckweeds can grow optimally at temperatures between 20°C and 30°C. Some species of duckweeds illustrate a decrease in the growth rate below 17°C [10]. Duckweeds can tolerate a wide range of pH (3.0-10.0), however, illustrate optimum growth in a medium of pH 5.0-7.0. Duckweed possesses the capability of growing either as autotrophs or heterotrophs by utilizing simpler organic compounds occurring in the sewage effluent as nutrients [11].

Duckweed mostly reproduces vegetatively (asexual reproduction), whereas flowering and seed germination i.e., sexual reproduction is rare [12]. Duckweed reproduces rapidly by budding [13]. They bud new generations (daughter fronds) from their reproductive pouches located at the base of the mother fronds [14]. Due to the extreme reduction of their bodies, duckweed requires minimum non-photosynthetic organs and could rapidly multiply through budding [15].

Under the optimum conditions, they could double their body mass in less than 48 hours [16]. The high rate of generation makes duckweed the most promising biological candidate for future food, water treatment, and several biotechnological applications. For example, *Lemna minor* happens to be the most commonly utilized entity in phytotoxicity testing, as adopted by several international standardization organizations [17]. The novel *Lemna* root-regrowth test occurs to be a rapid and reliable toxicity screening test of the wastewater effluents and hazardous pollutants in the natural waters.

The duckweeds are largely distributed to a variety of geographical and climatic zones except for the deserts and the permanently frozen polar regions. They majorly refer to the moderate climates of tropical and temperate zones. Many species of duckweed could survive temperature extremes, however, grows faster under warm and sunny climates. Their ability to largely adapt to different environmental conditions aids their wide distribution globally.

Duckweed occurs in abundance in various parts of Europe, North America, Asia, and Africa. Asia Pacific forms the dominant region in terms of production as well as utilization of duckweed for human and animal consumption. The utilization of duckweed has likewise, increased exponentially in Europe and America due to the increasing growth of wastewater treatment.

Under undesirable conditions such as nutrient starvation, drought, or low temperature, the duckweed meristem can generate dormant starch-rich fronds [9]. For example, *S. polyrhiza* produces dormant bodies – 'turions', which sink at the bottom of the aquatic bodies during adverse conditions such as low temperatures. With the reoccurrence of favorable temperatures during the spring, the new fronds are formed from the dormant bodies by utilizing starch for metabolism and begin floating on the surface of the water once again [18].

Figure 1. Duckweeds – Free-Floating Aquatic Plants

4 Applicability of Duckweeds in Africa as a Food Resource

A limited supply of quality feed appears to be the most important factor limiting livestock productivity in many Sub-Saharan African countries. The chief feed resource for grazing ruminants constitutes pastures and crop residues. According to the Global Forest Resources Assessment 2020, Africa has the highest annual rate of net forest loss during 2010-2020 accounting for 3.9 million ha [19]. The major causes of deforestation include overpopulation, agricultural expansion, overgrazing, and so on. Specifically, in East Africa, pasture lands have increased by 50% since 1980 [20]. The main goal of clearing forests to make way for additional pastures is to increase livestock production. However, many of these pastures and especially in the north of the Sahara desert occur to be heavily stocked which generates too little forage for the livestock. The extremely low productivity of the livestock in turn becomes one of the major determinants of poor nutrition among the people.

In Africa, it still occurs to be a common practice to keep as many cattle as possible, as an indicator of high social status and wealth. Likewise, the quality of the available feed happens to be quite low and the accessibility varies with the seasons. Consequently, in Africa, the commonest issue includes the shortage of animal feed and inefficient utilization of whatever is available. Therefore, a more sustainable and nutritive feed must be made available for feeding the livestock.

Africa has increased its agricultural area by more than one-third during the last 20 years (2000-2019), accounting for almost 52% percent of worldwide growth [21]. This rapid growth of arable land occurred largely by harming the forests and the natural ecosystem. For example, within 60 years the Ivory Coast has lost almost 90% of its forest cover. However, food insecurity still prevails rampant in Africa. According to FAO, Africa would need an additional 120 million hectares of arable land by 2050, along with pasture growth, in order to meet the rising demand for dairy and meat products [21]. This would definitely lead to more deforestation and environmental degradation. In order to protect our planet, it has become inevitable to cease any further environmental deterioration. It's time to switch to a more practical, environmentally friendly, and long-term method of sating animal and human hunger.

5 Nutritive Value of Duckweeds

Fresh duckweed comprises around 92-94% of the water. The duckweed cultivated under the ideal conditions, with regular harvests comprises around 5 – 15% of fiber content and about 35 to 43% of crude protein [22]. The protein constituents are 4.8% Lys, 2.7% Met + Cys, and 7.7% Phe + Tyr [23]. Duckweed could provide a full range of amino acids required by the human body. It comprises all nine essential amino acids, as well as several non-essential amino acids. The average values of the amino acids occurring in the duckweeds are at par with cereal grains, such as wheat, corn, rice, soy, chickpea, and lentils. For example, the tryptophan and methionine in duckweed appear to be higher as compared rest of the food resources mentioned [24]. The amino acid content varies among the different species of duckweed.

Duckweed contains varied kinds of carbohydrates such as starch cellulose, trace hemicellulose, pectin, etc. However, the specific carbohydrate content of the duckweed relies on the species and the growth parameters, nutrients available, and location.

The starch content records for 4-10% per dry weight, while the polyunsaturated fatty acids account for 48-71%. The starch content of duckweed plays a quite crucial role in survival capabilities as mentioned above. Additionally, the presence of resistant starch in some uncooked species (such as *S. polyrhiza)* resists digestion in the small intestine, but ferments in the large intestine proving beneficial for the gut health of humans.

The mineral content of the duckweed could be easily manipulated by adjusting the composition of the nutrient medium. Duckweed contains high levels of mineral content (such as Ca, P, Na, K, Mg, Fe, Mn, Cu, and Zn) as compared to the routinely utilized cereals and grains (such as chickpea, corn, rice, soybean, and wheat).

The graph below (figure 2) indicates the percentage of different chemical components in different species of duckweed.

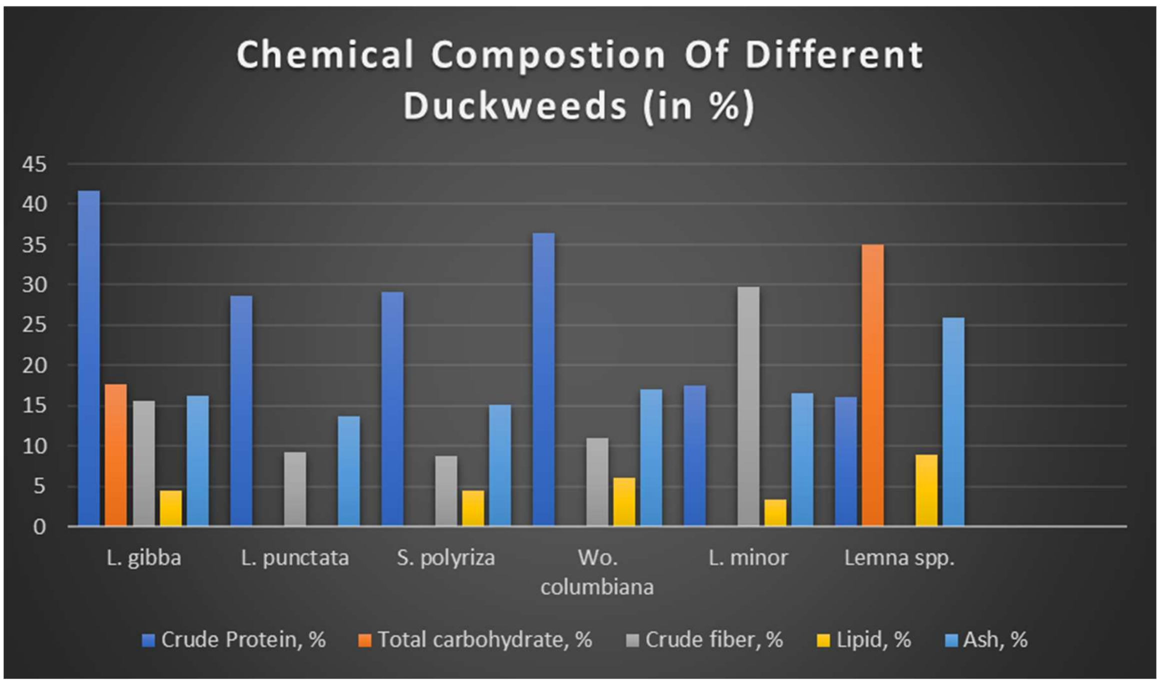

Figure 1 Chemical Composition of Different Duckweeds (designed by the author, data sourced from [25] [26] [27] [8])

Moreover, even the fatty acids distribution in duckweed varies among different genera and species. Duckweed comprises a larger portion of polyunsaturated fatty acids and monounsaturated fatty acids, while omega-3 and omega-6 occur to be the predominant unsaturated fatty acids in the duckweeds [24]. However, future research and studies must focus on a better understanding of the functional properties and stability of unsaturated fatty acids in duckweeds.

Likewise, cultures of duckweed contain a high concentration of pigments, predominantly beta carotene, and xanthophyll, making the duckweed meal a valuable supplement for poultry, aquafeed, and other animal feed. Additionally, they also form a rich source of minerals, vitamins, and phytochemicals [8]. Carotenoids appear to be the major phytochemicals occurring in the genus *Wolffia*, with lutein and β-carotene accounting for the major ones (recorded values – 40-80 mg/100 g and 10-30 mg/ g (dry weight basis), respectively [23]. The sterol content of the genus *Wolffia* accounts for 2.4–5.3% largely comprising β-sitosterol, campesterol, and stigmasterol [28]. Even *L. minor* was reported to comprise a good content of saponin, flavonoids, and alkaloids [29].

6 Duckweed as Animal Feed

Duckweeds offer a sustainable approach to improving the quality and quantity of animal feed. Duckweed has been largely supplemented to animal feed for preventing incomplete nutrition obtained from traditional feeds and promoting animal growth, for example, research has been conducted to partially replace fish meal, soy meal, alfalfa leaf meal, and others with duckweeds in animal feed, providing fairly feasible results [30]. Commercial interest in duckweed for supplementing animal feedstock has increased in recent years, owing to the increasing fishmeal price and availability issues, GMO controversy, and general increasing interest in exploring more sustainable feed production overall.

Several studies indicate the high suitability of duckweed as animal feed. Duckweed comprises a high content of protein, amino acids, and several micro and macro-nutrients. Fresh as well as dried duckweed appears to be readily consumed by poultry birds as well as cows, sheep, goats, swine, and fish [31]. One of the studies illustrates, that the replacement of sesame oil cake with different percentages of dried duckweed (such as 0, 3, 6, or 9%), improved the flattening of the Vencobb broiler chickens fed with 3 or 6% of duckweeds [32].

Similarly, an experiment conducted (by A. Haustein *et al,* 1994), concluded that the utilization of 5% of duckweed (in the standard diet) as an additional protein source for broilers, had a positive result, indicated by higher body weights at the end of the experiment as compared to the control bird (no duckweed fed) [33]. Equally, the replacement of inorganic salts with dried duckweeds enriched with the trace elements in the diets for Lohmann Brown layers resulted in improved egg quality, as compared to the group of layers not fed with duckweeds [34]. Similarly, the inclusion of *Lemna gibba* in the diet of commercial strains of laying hens (Topaz layers and Leghorn HyLine) at 0, 15, 25, and 40%, maintained the egg production and egg weight as similar to the control hens at all levels [35]. The eggs from Leghorn hens fed with 15% and 25% *Lemna* illustrated higher protein content in eggs than the control eggs. Equally the addition of duckweed to the diet improved the yolk pigmentation. Therefore, duckweed could be an important substitute for soybean and some fish meal diet for hens, especially in countries where chicken feedstocks are imported.

The high levels of carotene content of the duckweed have been illustrated to deepen the yellow colour of the broiler meat and skin. Some of the species of duckweed stimulate the birds to eat more due to their high palatability.

It is however, important to note that although duckweed feed improves the weight gains up to 6% of the protein in the final diets for broiler chickens, studies have demonstrated that the growth of the young broiler chicken tends to be retarded by increasing the levels of dried duckweed meal in the diet [36]. This could be attributed to the inability of the young birds to consume a sufficient amount of the duckweed, due to its bulkiness and low DM content [37]. This indicates that the young birds must be carefully fed with duckweed.

Moreover, 10-20% crude protein from soybean meal was observed to replace the crude protein from *Lemna spp*. in Japanese quails' diet without causing any adverse effect on the intake, weight gain, feed efficiency, and carcass dressing percentage [38].

Several studies likewise, reported the beneficial utilization of duckweed for farm animals. A replacement of soybean meal in piglet diet by duckweeds at different percentages such as (0%, 20%, 40%, or 60%) illustrated high body weight gains of piglets receiving 40 and 60% of duckweed diets as compared to the animals receiving soybean meal as the only source of protein [39]. An experiment conducted (by D. T. Hang, 1998) concluded that feeding Mong Cai pigs with duckweeds (*Lemna. minor*), illustrated higher body weight, better live weight gain, and better feed conversion ratio as compared to the pigs fed with the sweet potato vines [40]. A similar study involving the incorporation of 10% of duckweed as a supplement in the pig ration by replacing sorghum and soybean meal, illustrated improved production results [41]. The duckweed concentrate occurs to be as nutritive as compared to soybean and fish meal and could be possibly included in the diets of the young pigs.

Furthermore, the Merino ewes illustrated a high willingness to ingest both fresh and dried duckweeds and had no negative impact on their wool yield, rate of wool elongation as well as fibre diameter as compared to the control groups fed with oaten chaff diet [42]. Likewise, the haematological and antioxidant responses of the dairy cows fed with a combination of feed and *Lemna minor* as a mixture occurred to improve their performance [43].

An experiment with African dwarf goats concluded that the supplementation of fresh duckweed in the diet improved nitrogen retention as compared to the control diet comprising only guinea grass [44]. Duckweeds were observed to be nutritionally comparable to the soybean meal and posed no adverse effect on the rumen pH, amount of ammonium ions, and volatile fatty acids [45].

Several types of duckweeds such as *Spirodela*, *Lemna,* and *Wolffia* were illustrated to be consumed by the ruminants [46]. However, these duckweeds differ in their composition. The extent of the duckweed digestibility indicated that dry matter and crude protein occur to be highly degradable in the rumen, however, this demands further research to assess the level of duckweed supplementation as cattle feed.

The duckweeds equally appear to be beneficial for feeding the fish. For example, body analysis of the body composition of tilapia fed with a standard diet supplemented with dry and fresh duckweed illustrated a greater phosphorus and protein content, and lower lipid content as compared to the control groups fed with only a standard diet (containing fishmeal, corn, wheat, wheat bran, fish oil diamol, and premix) [47]. Utilization of the duckweed (*Lemna minor*) powder in the polyculture resulted in higher production of fish such as rui (*Labeo rohita*), mrigal (*Cirrhinus cirrhosus*), and silver carp (*Hypophthalmicthys molitrix*) [48]. Similarly, one of the studies indicated that solar-dried duckweed (*Spirodela polyrrhiza* L. Schleiden) with dietary inclusion of 30% as a replacement for fish (*Oreochromis niloticus* L.) meal promoted fish growth and proved to be cost-effective [49]. The duckweed forms the most convenient fish feed owing to the under-mentioned reasons:

- Rapid growth in the local polluted ponds.
- Feasibility of being fed fresh, owing to the ease of harvesting.
- Efficiently consumed by fish such as tilapia and carp.
- Economically a viable solution.

Source: R. A. Leng, J. H. Stambolie, and R. Bell, "Duckweed-a potential high-protein feed resource for domestic animals and fish," Livestock Research for Rural Development, vol. 7, no. 1, p. 36, 1995.

The referenced studies and experiments prove the high applicability of duckweed as animal feed. However, the percentage of the diet replacement, the extent of digestibility, acceptability, and health benefits of several different species of duckweed must be explored further before constituting the duckweed as the prime protein source for animals.

7 Duckweed as Potential Human Food

Duckweeds are already being served as human food in several Asian countries including Laos, Thailand, and Myanmar. In these countries, the rootless duckweed *Wolffia globosa* by different local names such as '*Khai nam', 'Kai-pum', or 'Kai nhae'* (water eggs) are sold in the vegetable markets. The plant is eaten as chips, bread, and in soups or stir-fries in these regions. A protein-rich diet such as duckweed plays an important role as the food resources in these regions, which have more starchy food, such as rice as their staple. One of the research studies conducted on the nutritional content of duckweed (*Lemna paucicostata* hegelm.) in the Kainji Lake area, Nigeria concludes that a fair content of crude protein (26.3% to 45.5% of plant dry mass), and essential amino acids (surpassing the FAO reference) occurs in this duckweed [50]. This duckweed could be potentially utilized as human food in Africa.

RuBisCO (ribulose-1, 5-bisphosphate carboxylase), occurs as the major protein in the duckweed, forming a necessary source of essential amino acids. RuBisCO possesses high nutritional value and is non-allergenic [51].

A partial substitution of wheat flour with duckweed flour could greatly enhance the nutritional profile of conventional cereal foods along with several health benefits such as the prevention of chronic diseases, owing to a better amino acid profile and higher content of vitamins, minerals, and antioxidants compared to wheat [24]. The processed and powdered duckweed could be added to baked products, sport nutrition drinks, pasta, and snacks [9]. Similarly one of the randomized controlled trials concluded that Mankia (a high-protein strain of *W. globosa*) may provide a high-quality substitute source for animal-derived proteins [52]. Equally, *Wolffia globosa* Mankai may serve as a promising alternative source of plant-derived protein with potential beneficial postprandial glycemic effects [53]. Additionally, it has been reported that the bioavailability of the essential amino acids in *Wolffia globosa* was equal to the well-proven animal (soft cheese) and plant (peas) iso-protein source [52].

Likewise, duckweed naturally synthesizes various biochemical compounds including carotenoids, phytosterol, and other pigments, possessing high antioxidant and anti-inflammatory properties. These bioactive compounds could be largely utilized in several foods and nutraceuticals to combat cancer, cataract, as well as free radicals. Additionally being rich in vitamins, amino acids, and micronutrients, duckweeds could be effectively utilized for fighting the wide-prevalent malnutrition in Africa, especially in young children.

Duckweeds likewise, have a high level of flavonoids, which could potentially provide several human health benefits. They could largely impart antiviral, antifungal, antibacterial, antihepatotoxic, anti-osteoporotic, antiulcer, and antiproliferative effects [54]. Additionally, flavonoids illustrate several other properties including immunomodulation, and apoptotic effects, and reduce the risk of carcinogenesis, inflammation, atherosclerosis, and thrombosis. The antioxidant capacity of flavonoids essentially protects the cells from the reactive oxygen and nitrogen species, which could cause damage to biomolecules such as DNA, lipids, and proteins [55].

The high content of carotenoids in duckweed imparts several health benefits in humans. Carotenoids and vitamin E, play a major role in opposing chronic inflammation [56]. Furthermore, Zeaxanthin, lutein, and β-carotene effectively inactivate, and thereby detoxify, reactive oxygen species, which causes several cellular damages. The carotenoids equally, regulate genes that function to induce the immune response. Some of the carotenoids along with additional dietary nutraceuticals have the potential to directly oppose obesity [57]. β- carotene - the precursor of vitamin A, which plays a vital role in several biological processes including vision. Similarly, lutein improves the age-related macular disease responsible for causing blindness and vision impairment. Other leafy green and green plant products containing lutein and β- carotene, contain very little to no zeaxanthin when they reach humans, due to the lower accumulation of zeaxanthin in fast-growing terrestrial plants as compared to slow-growing evergreen with edible leaves. Currently, high levels of zeaxanthin occur in egg yolk, corn, and orange pepper. However, duckweed may serve as an alternative, eco-friendly food source with high levels of lutein as well as zeaxanthin.

Duckweeds also encompass a nutritionally favorable ratio of polyunsaturated omega-6- and omega-3- fatty acids that impart immune-response-initiating and immune-response-terminating effects respectively [58]. One of the studies investigated the fatty acid distribution in *S. polyrhiza*, *L. punctata*, *L. minor*, *Wa. hyalina*, and Wo. microscopica and observed that, *Wo. microscopica* had a higher amount (71.1%)of polyunsaturated fatty acids (PUFA) [23], which aids in the reduction of LDL (bad cholesterol) in humans.

One of the duckweed species (*Spirodela polyrhiza*), finds its noteworthy spot in treating urticaria, acute nephritis, influenza, and inflammation in Japan, Korea, and China [54]. Several flavonoids occurring in the *Spirodela polyrhiza* extract makes this duckweed an important component of traditional medicine.

Thus, nutritionally dense duckweeds could be the next 'Superfood', which imparts several health benefits to humans with a maximum environmental footprint and sustainable cultivation process.

8 Criticality of Duckweeds as Human Food

Though duckweed could form the 'Novel Food Source' and possess the capability of replacing animal-derived protein, which has a significantly high environmental impact, several constraints should be addressed effectively and explored further. The acceptability of duckweeds in a larger portion of the world seems to be limited due to the presence of high content of crystallized oxalic acid/calcium oxalate, imparting a negative taste, as well as the difficulty to separate the pathogenic organisms such as worms, worms, snails, protozoa, and bacteria, form plants [59]. The duckweed also has a very high phytoremediation property, which makes their cultivation (intended for human consumption) in wastewater unfeasible, as they tend to accumulate a large proportion of pollutants.

Some of the duckweed species such as *L. minor* comprise a considerable level of anti-nutrients such as oxalate and phytate, adversely impacting the palatability and digestibility of the duckweed. Several processing techniques such as drying, soaking, cooking, or using degrading enzymes already being utilized for reducing the anti-nutritional content of other vegetables and plants, must be explored for neutralizing the anti-nutritional content of duckweed. Similarly, calcium oxalate in the duckweed seems to largely rely on the calcium content of the water on which they are being cultivated. Lowering the calcium content of the growth media can most likely lower the content of calcium oxalate formed in the duckweeds. It seems practical and feasible to place the duckweed in soft water for a reasonable period to lower the accumulation of calcium oxalate in these plants.

Moreover, the acceptability of the duckweed could be likely improved by disseminating the nutritional and environmental benefits of the duckweed. The duckweeds were reported to possess no detectable anti-proliferative or cytotoxic effect, as the first major step to exclude any harmful effects of duckweed on humans [60]. However, further exploration into the usability and digestibility of duckweed as human food, and the several health impacts with many clinical trials requires to be conducted for making duckweed the mainstream staple food for humans.

9 Applicability of Duckweeds for Treating Wastewater

Wastewater treatment status in Africa

Wastewater occurs as a combination of one or more domestic effluents comprising blackwater and greywater, effluents from commercial developments, industrial effluents, stormwater, and several other urban and agricultural runoffs**.** The ever-increasing population, urbanization, and several other economic activities form the major determinants of the increase in global wastewater volumes with the trend expected to be continued, including in Africa.

The wastewater streams responsible for major water pollution in Africa, include municipal wastewater, agricultural wastewater, industrial wastewater, urban stormwater run-off, and hospital wastewater [61].

Africans generate a significant amount of wastewater per day. For example, across West African cities, one person produced nearly, 20-150 liters of wastewater per day, and this value is projected to be tripled in the next 30 years [62]. Though several advances have been made in wastewater treatment and reuse, many places in east and west Africa treat less than 5% of the wastewater. There occurs a significant lack of appropriate wastewater treatment in most African countries, especially sub-Saharan Africa. The untreated sewage effluent has resulted in tremendous pollution around urban rivers and groundwater resources in Africa. For example in Kenya, most of the municipal wastewater treatment plants releases partially treated or untreated wastewater containing high levels of organic matter in the aquatic bodies, further deteriorating the already scarce freshwater resources [61]. The same situation imitates itself across most of the places in Africa such as Dar es Salaam, Accra, Khartoum, Harare, Maputo, and Kampala. The centralized as well as decentralized wastewater treatment systems in most parts of Africa fail to treat the wastewater to sufficient levels.

Challenges in wastewater and fecal sludge treatment in Africa:

Several challenges and adverse impacts on the operation of the wastewater and fecal sludge treatment plants in major countries of Africa. The major challenges faced during wastewater treatment in Africa are depicted in figure 3.

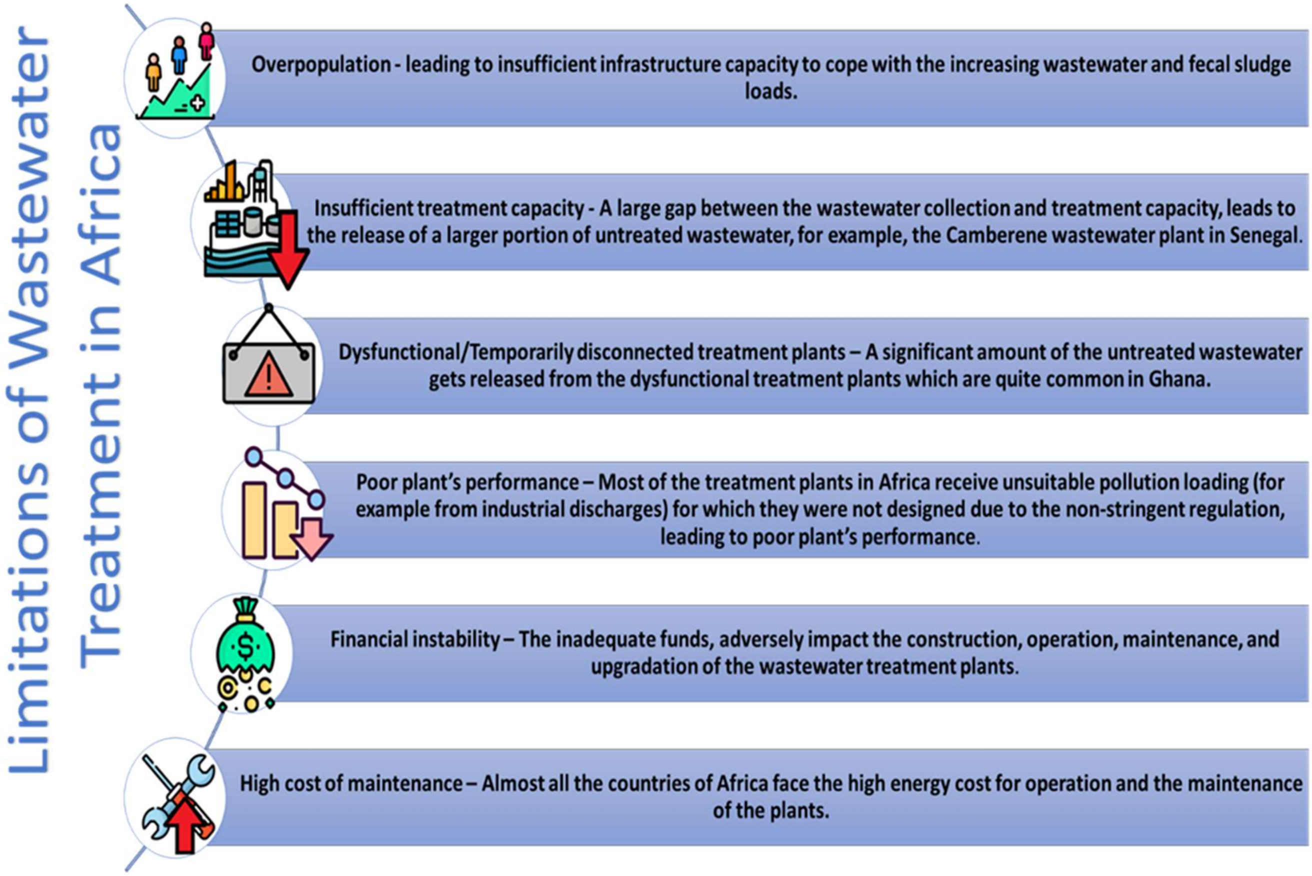

Figure 2 Major Challenges faced by Africa for Treating the Wastewater (designed by author after [63])

The wastewater treatment calls for further advancements which are cost-effectively as well as energy efficient.

One such alternative includes the utilization of duckweed – the smallest aquatic plant for the treatment of wastewater.

10 Potential of the Duckweeds to Treat the Wastewater

Duckweed plants form a most valuable alternative for their utilization in sustainable wastewater treatment owing to their rapid growth, ease of harvest, and as a protein source. As compared to other aquatic macrophytes, duckweeds have several advantages as stated under as a wastewater-treating agent:

- The duckweed has a high rate of nutrient uptake and could tolerate wastewater with high levels of nutrients [64].
- The duckweed multiplies vegetatively and accumulates biomass most rapidly.
- The duckweed biomass comprises high protein content which could be further utilized as animal feed. [22].

Duckweed-covered wastewater systems could attain BOD and COD removal rates between 50 and 95% [65] [66]. Within the duckweed system, the degradation of the organic matter gets enhanced through both the additional oxygen supply and the additional surface area for bacterial growth [67]. The duckweed pond develops a thick floating mat of duckweed (*Lemna*), that uniformly covers the surface of the water and thereby, prevents the growth of algal blooms and water evaporation. This helps in maintaining the clear suspended solids effluent, pH, and dissolved oxygen condition, which in turn preserves the bacterial growth important for the organic degradation of the pollutants [68].

The removal of nitrogen occurs either by direct uptake by the duckweed with subsequent harvesting, volatilization of ammonia, or bacterial nitrification/denitrification [69]. However, the volatilization plays a meager role owing to the pH lower than 8-9. Through direct uptake, duckweed uses NH_3-N, NO_2-N, and NO_3-N as its growth nutrients and removes these nutrients from the wastewater [70]. Nitrification of ammonia-nitrogen could occur in the oxidized root zone of duckweed, whereas, denitrification tends to occur in reduced environments in the water column or the sediments. However, due to the lower depth of the aerobic layer, the nitrification step of the nitrification/denitrification process occurs to be a rate-limiting step. In order, to obtain a high rate of nitrogen removal through nitrification/denitrification, supplemental aeration is needed. Likewise, the phosphorous gets eliminated from the wastewater through biomass accumulation. One of the research account for 74% and 77% removal rates of total nitrogen and phosphorus, respectively, by duckweeds [71]. Suspended solids, BOD, and pathogens removal mechanisms appear to be similar to those encountered in conventional wastewater treatment ponds (that includes, sedimentation or filtration for SS, anaerobic microbial decomposition for BOD, and filtration, adsorption by plant roots or predation by micro-organisms for BOD).

Ammonia, both in ionized and unionized forms imparts toxicity to duckweeds. However, duckweed could potentially treat the wastewater containing high levels of ammonia as long as the certain levels of pH do not exceed.

The duckweed mat with attached bacteria and algae appears to be responsible for three-quarters of total nitrogen and phosphorous loss in the shallow system, irrespective of the loading rates [67].

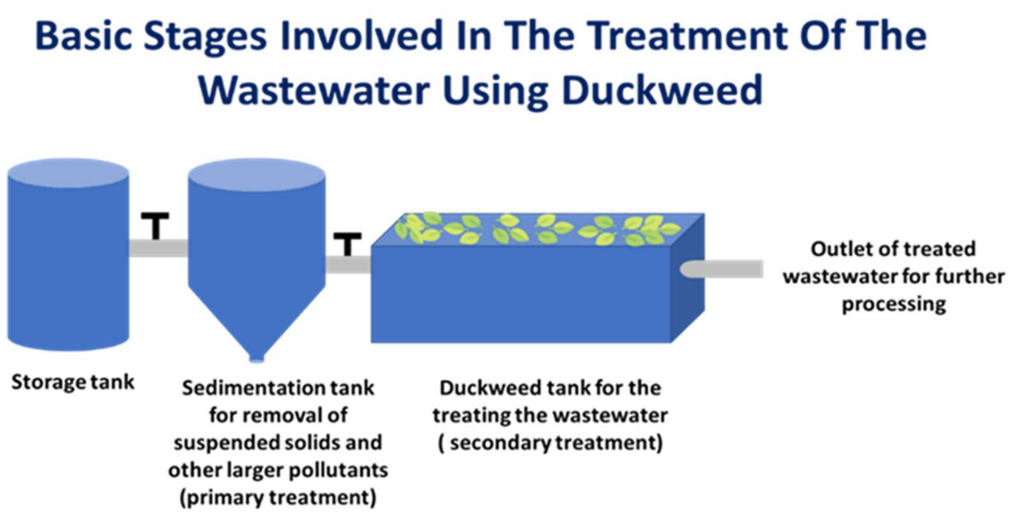

Figure 4. *Schematic diagram illustrating the stages involved in the treatment of the wastewater by the utilization of the duckweed(designed by the author after [70])*

The final removal of the pollutants occurs by harvesting the duckweed. The duckweeds if cultivated in domestic wastewater lacking heavy metals and other hazardous compounds, then it could be largely utilized as agricultural fertilizers as well as in the production of green compost. Alternatively, the harvested biomass could be preferably utilized as the feedstock for anaerobic digestion for the production of biogas, which could solve several issues related to the energy crisis in Africa.

Simple cost-effective wastewater treatment by the duckweed-based system must primarily involve the three components, such as storage tank, sedimentation tank, and duckweed tank as illustrated in figure 4 on the previous page.

11 The Practicality of Duckweed-Based Wastewater Treatment Systems

Most of the settable solids appear to be removed in the sedimentation tank, which improves with the higher retention time. The remaining organic matter as well as suspended solids get eliminated in the duckweed tank. The duckweed tank/ basin should be constructed with a large length/width ratio (greater than 10), in order to achieve the maximum growth of the duckweeds as well as to simplify the harvesting process. Although dense, the duckweed mat formed on the surface of the wastewater could be displaced by the wind, which could largely impact the treatment efficiency. Artificial windbreaks, emergent aquatic macrophytes, trees, or floating barriers may be utilized to minimize the disturbance caused by the wind current [69].

Furthermore, duckweed harvesting occurs to be fairly easy as they don't form any structural unity, therefore no cutting or chopping is needed. The harvesting could be done by physical methods, such as raking, mechanical skimmer devices, and aquatic harvesters. However, manual harvesting by utilizing a rake seems to be a tedious job and applies only to smaller ponds.

Not only the domestic wastewater but the agricultural wastewater (more specifically the tailwater) could be largely used for cultivation of the duckweed for several purposes. Roughly 65% of the African population relies on subsistence farming, which generates a significant amount of tailwater, which goes wasted most of the time. The tailwater refers to the water which is left after being applied to the farm for irrigation purposes.

The tailwater could be collected in ditches and could be delivered to a storage reservoir through pipelines, which include a pumping and pipeline system. This stored water could be further treated by utilizing duckweeds to obtain high-quality purified water, which could be further utilized as the source of fresh water for growing duckweed for human consumption (largely *Wolffia*).

We can thereby, utilize the wastewater for growing duckweed which would not only purifies the water (for recycling purposes) but would likewise, provide a source of fresh water for growing the specific types of duckweed important for human consumption to mitigate food insecurity in Africa.

12 Conclusion

According to various research cited in the paper, it is clear that duckweed has great potential for use as a source of food and feed for both people and animals. Duckweeds are the most potential candidates for being used as fuel for energy production processes like biogas due to their high rate of replication. However, further research and proof are needed to prove that duckweed is a suitable primary dietary source. Similarly, it is necessary to investigate some low-cost techniques for enhancing the flavor and digestion of duckweed as nourishment for humans.

However, other salt-tolerant species might be studied and used for better growth in the main drought-stricken regions. Duckweed may be the most practical and approachable solution for alleviating food insecurity in Africa. Additionally, to grow duckweed for human consumption, the wastewater in Africa must first be highly cleansed before being used to produce duckweed food. A sophisticated processing plant is needed to further prepare the duckweed to reduce bacterial contamination and provide extremely nutritious human food. To cultivate duckweed in an enclosed, controlled environment, further research needs to be done on hydroponic and aeroponic indoor vertical farming techniques. By using duckweed in Africa, and taking into account all the important factors listed, the rising food insecurity might be significantly reduced.

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