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Coupling Aquaponic Systems with Sustainable Energy and Food Generation for a Tropical Climate, in Panama: A Review

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Abstract - Nowadays society faces different problems regarding populational growth, energetic consumption increase, and food shortages; currently more than 66% of the world population is undernourished. Additionally, present-day food production is becoming constrained due to the scarcity of arable land, freshwater, and the chemical contamination of fertilizers. This scarcity of resources is increasing along with the rapid growth of the human population around the world. This paper performs a systematic review via a bibliometric analysis employing VOSviewer, observing and analyzing scientific research trends in terms of sustainable food and energy generation. We present diverse aquaponic systems and their survival and efficiency rates. In terms of energetic generation, we discuss on the possibility of employing a plant micro fuel cell (P-MFC) with Oryza sativa to power up, resulting in the harvest of both rice and spinach. In terms of fish, the Oreochromis niloticus was selected due to its adaptability, survival rate, and local presence. Additionally, in the context of the scarcity of freshwater, we propose employing saline water in our system.
Keywords - aquaponics, biomimicry, electrical generation, plant microbial fuel cell.

I. Introduction

Currently, world energy consumption comes from three main economic sectors, transport, industry, and construction [1]. A substantial part of global energy consumption comes from buildings, which is expected to increase to 32.4% of total energy consumption by 2040 [2]. In addition, by 2050, the population of all the world's cities will receive more than 2.5 billion additional people, which means that around two-thirds of the world's population will live in cities in the next three decades [3].

Population growth in urban areas will result in higher energy consumption in buildings. Energy is derived from both electricity and fossil fuels (gas, coal, and oil). Electricity and fossil fuels account for 54% and 43% of total building energy, respectively [4].

As a result, a significant proportion of buildings will emit a large number of greenhouse gases (GHG) for their operation. It is known that an increase in these GHG emissions will intensify climate change, leading to further negative impacts on many aspects of the natural environment. Therefore, energy-efficient design and operation will play a critical role in reducing GHG emissions in buildings.

On the other hand, in this work, we will focus on hot and humid climates such as Panama, where the biggest problem in these areas is the humidity which must be taken into account when implementing the different passive strategies [5]. As part of the developing countries, Panama has shown strong economic growth during the last decade.

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According to the World Bank, between 2001 and 2013, its average annual growth rate was 7.2%, more than double the average in Central and South America [6]. According to estimates, energy consumption in Panama will increase by 188% between 2015 and 2050, if measures are not taken to reduce consumption and improve energy efficiency [7].

However, it is important to highlight that overpopulation does not only impact the electricity sector and buildings, but also food shortages. Currently, more than 66% of the world population is undernourished according to the World Health Organization (WHO)[8] and the Food and Agriculture Organization of the United Nations (UN) [9]. The number of malnourished registered in 1950 was only 20% of the world population and now it has more than tripled. Malnutrition inhibits the mental development of children, reduces human productivity, and is the leading cause of death in the world today according to the UN and WHO [8].

Current food production is becoming constrained due to the scarcity of arable land, freshwater, and scarcity of fertilizers that rely on fossil energy for their production (nitrogen) or their extraction and processing (i.e., phosphates, potassium, micronutrients). This scarcity of resources is increasing along with the rapid growth of the human population around the world.

Given the problems we currently face, we propose evaluating a biotechnological system for electricity generation that allows sustainable local cultivation. For this, a systematic review of various biomimetic alternatives was carried out. Seeking to follow the principles of biomimicry, eco-design, and circular economy.

II. METHODOLOGY

For the systematic review, the methodology employed here follows a bibliometric analysis based on two main aspects, sustainable crops, and bioinspired energy generation.

A. Search Strategy

The literature search strategy implemented here consists of a combination of keywords and logical operators, i.e., AND and OR. The keywords chosen are terms related to the principal topic, applying biomimicry to obtain sustainability in crops and energy generation, and some secondary terms, which are synonyms of the previous terms. Fig. 1 displays the approach followed for the document selection.

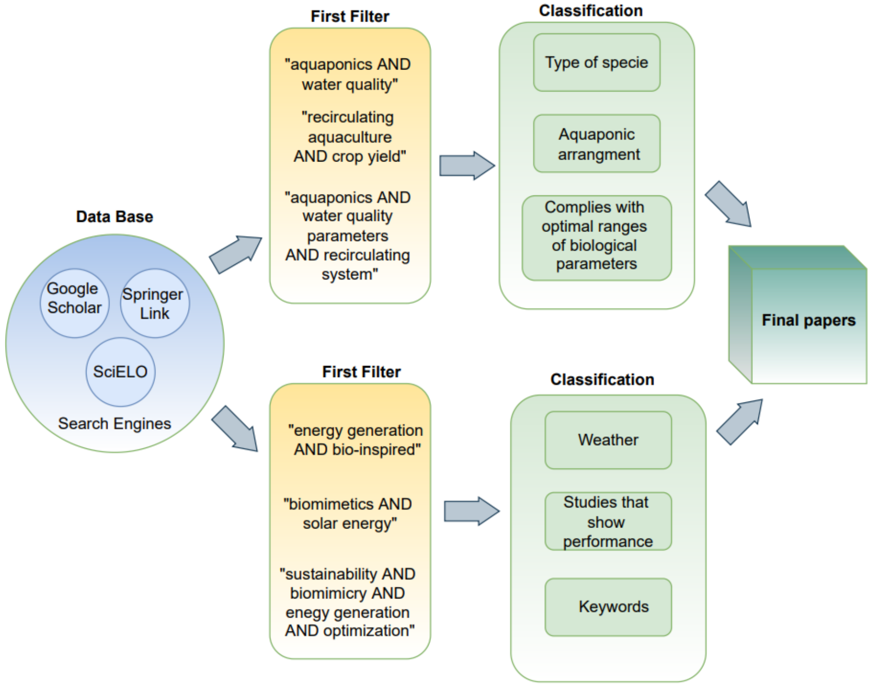

Fig. 1 Approach Implemented for Keyword Generation.

B. Bibliometric analysis

The bibliometric analysis is focused on the main aspect of this investigation: bio-inspired actions toward aquaponics with sustainable energy and food generation. The VOSviewer software, version 1.6.19, was used to create a map from the bibliographic database for a systematic presentation and analysis.

The following keyword combinations with logical operators were used for the search: "aquaponics AND water quality," "recirculating aquaculture AND crop yield," "aquaponics AND water quality AND recirculating system," "energy generation AND bio-inspired," "biomimetics AND solar energy," "sustainability AND biomimicry AND energy generation AND optimization." The map was created through a keyword co-occurrence analysis using the full counting method. Of 3103 keywords, 83 met the threshold test, suggested by the software algorithm, with a minimum number of occurrences of five. The keywords with the greatest total link strength will be selected and displayed.

III. RESULTS ANALYSIS AND DISCUSSION

A. Current state and tendency of the specific fields

Fig. 2 depicts the overlay visualization map generated with VOSviewer.

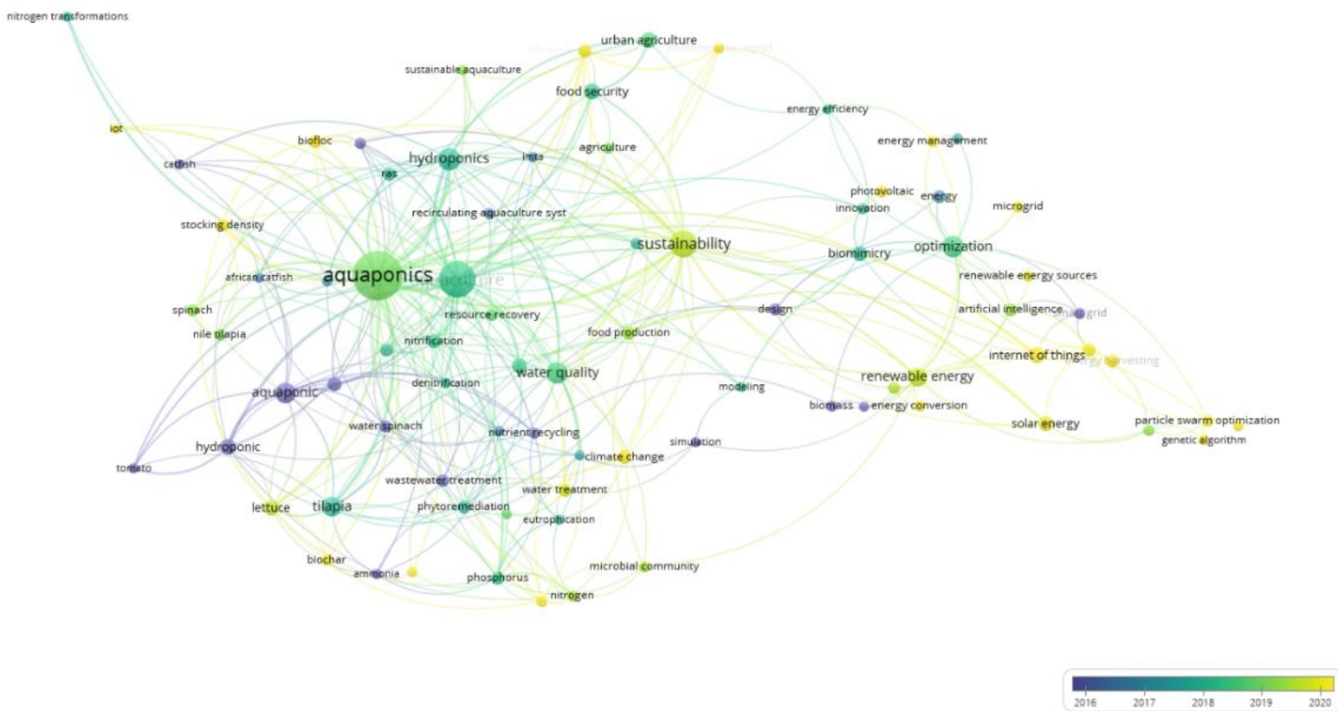

Fig. 2 Overlay visualization by the average publication year of main terms in aquaponics with sustainable energy and food generation.

Here we can observe how terms such as biomimicry, even though it is intrinsic to aquaponics, is no longer used (regarding the timeline color bar). This could be because the definition encloses very specific metrics that are very difficult to follow.

In the overlay visualization, we can also see how in recent years the trends move away from nutrient recycling and removal (in purple). While turning towards the internet of things, life cycle assessment, renewable energy, and sustainability (in yellow). This indicates the current priority is developing an improved, optimal, and self-sustainable system.

Here, the crops mentioned include only lettuce, tomato, and spinach, meaning these may be the most commonly employed in aquaponics. While in terms of fish, tilapia, and catfish are mostly selected.

It is important to keep in mind that the most common term was aquaponics (in green, by the size of the bubble), and it was found with an occurrence of 113; this gives us a better perspective as to how many times the other smaller bubbles with different terms have been applied.

B. Aquaponics

Aquaponics consists of integrating the aquaculture system with hydroponics, it is defined as the cultivation of fish and plants in a recirculating system [10], which could serve for the sustainable production of food in polyculture. Which increases diversity and final production, and the possibility of obtaining products with phytosanitary quality and with important socioeconomic impacts by obtaining economic benefits [11]. The biological principle is based on the fact that the nutrients required for the growth and development of plants are very similar to the waste produced by aquatic organisms [12]. Due to this same principle, there are various parameters that we must measure regularly. From the perspective of crops, aquaponics presents advantages compared to soil production. The authors in [13] showed higher yields with cucumber (7.3 vs 4.6 kg/m^2) but lower production with tomato (4.6 vs 6.1 kg/m^2). While the authors in [14] showed higher productivity in basil with yields of 1.8–2.0 kg/m^2 (0.6–1.0 kg/m^2 in soil) and okra with 2.5–2.9 kg/m^2 (0.15 kg/m^2 on the ground).

Aquaponics also shows higher productivity compared to hydroponics in mature systems for tomato (31–59 vs. 41–45 kg/m^2) and cucumber (42–80 vs. 50 kg/m^2) provided the Nitrogen-Potassium (N: K) ratio is close to of 1 [15]. For higher N: K ratios, certain fruit plants can still perform well against hydroponics, such as eggplant (7.7 kg vs. 8.0 kg/m^2) and tomato (23.7 vs. 26.3 kg/m^2), but cucumber seems to show reduced yields (3.3 vs. 5.2 kg/m^2) [16]. The results of various selected studies will be broken down in greater detail below.

Among the studies evaluated, we first present the physicochemical characterization of a brackish tilapia effluent to evaluate the growth of three types of vegetables [17]. These are Cuban oregano (*Plectranthus amboinicus (Lour.) Spreng*), vaporub (*Petroselinum purpuratus Harv*), and mint *(Mentha X verticillata L.*). Regarding the fish species, 700 tilapia hatchlings (*Oreochromis niloticus x O. aureus*) were used.

Based on the results of this study, the oregano plants in aquaponics showed lower heights compared to traditional sowing and the diameter of the stem showed significant statistical differences ($p < 0.05$) between both systems. In the case of vaporub, the aquaponic system presented a maximum height of 20 cm on day 28. However, it is important to note that the plants became stressed due to salinity, which led to their death. Meanwhile, in the traditional system, a constant height was maintained. Regarding mint, its height in aquaponics and traditional planting showed significant statistical differences ($p < 0.05$); however, the height was comparable in the evaluation period, and in contrast, the aquaponics plants showed greater stem diameter.

In terms of the fish, in the beginning, the biometrics showed a total initial weight of the fingerlings on average of 0.7 g and at the end, they reflected an average weight gain of 206.01 kg on day 120. It is worth mentioning that in tilapia culture in aquaponics, no water exchanges were performed showing a survival of 91.10% under these conditions.

Based on these results, we can observe how of the three herbaceous plant species evaluated, peppermint (*Mentha X verticillata L.)* showed a comparable development between both planting systems. This work provides knowledge about the cultivation of herbaceous plants in brackish conditions, common in coastal farms. Which presents alternatives for integral production to aquaculture companies.

Currently, the lack of good-quality water for human consumption and agriculture is a great challenge for arid and semi-arid regions. In these areas, the availability of good-quality water is severely limited by low precipitation and high evapotranspiration [18]. In addition, the overexploitation of good-quality water resources has resulted in lowering water levels and increased salinization [19]. Salinization of water is a global concern and is most serious in arid and semi-arid areas, where groundwater is the main source of water [20].

In the context of freshwater scarcity and increasing salinization, efficient water conservation technologies, and strategies should be developed for the best utilization of saline groundwater in agriculture and related activities to alleviate pressure on freshwater resources [21]. Fish and crustacean aquaculture using inland saline groundwater opens a new route to convert underutilized saline groundwater into productive resources [22].

This study was carried out to find the right salinity for the best growth and survival performance of Nile tilapia (*Oreochromis niloticus*) with spinach (*Spinacia oleracea*) in an aquaponic system. The experimental design consisted of inland saline groundwater with salinities of 3, 6, and 9 g/L as treatments and freshwater as controls [23].

Spinach was harvested twice during the study, in the first harvest the highest yield was observed in freshwater followed by 3, 6, and 9 g/L, but in the second harvest, the highest yield was observed in 9 g/L followed by 6 g/L, 3 g/L, and fresh water. *Spinacia oleracea* can tolerate moderate salt concentrations [24]. This is why the reduced spinach yield at salinities of 3, 6, and 9 g/L compared to freshwater in the first harvest may be due to an initial salinity shock and the greater increase in yield in the second harvest of the highest salinity (9 g/L) can be attributed to the achievement of adaptation.

During plant exposure to salinity, the water balance mechanism is initiated and results in decreased osmotic potential and turgor, which in turn regulate further adaptive responses through chemical signals [25], and growth can be restored once the turgor has disappeared [26]. Deep seawater can be used as a nutrient supplement and could achieve better fruit quality. Yield reduction in the second crop of spinach grown in freshwater may be due to nutrient depletion, mainly potassium [23].

The final mean biomass was statistically similar at 9 g/L (5 kg/m^3), 6 g/L (4.92 kg/m^3), and 3 g/L (4.68 kg/m^3). Based on overall production performance and water quality parameters, a salinity of 9g/L was found to be the best for integrating Nile tilapia and spinach in an aquaponic system [23].

In another study, [27] maintained a temperature range (23.61-31.2°C) through the support of water heaters, thus maintaining optimal conditions for fish growth. Here, a survival rate of fish greater than 90% was achieved (93.81% for fingerlings, 94.29% for juveniles, and 91.67% in the case of adults). Concerning tomatoes, the observed growth percentage represents 68, 83, 80, and 81 for fingerlings, young, adults, and a case of hydroponic control respectively. Being the young fish tank the best performance. The survival rate showed the same behavior as the growth of tomatoes. The highest value was for tomatoes in the fingerling system (98.33%), followed by vegetables grown in the water together with young tilapia (93.33%) and finally, the lowest survival rate was in the tank with adult tilapia (91.66%). As a result of this case, it should be noted that pH values in the range of 7 to 9 were acceptable for tilapia, however, not for tomato growth [28].

Despite this, it was decided not to adjust the pH levels in the system to evaluate the performance of both species without the addition of external agents, except in the hydroponic case. Therefore, the best performance was given in the hydroponic tank due to the nutrient solution for crop growth and pH adjustment. Concerning aquaponic systems, the greatest growth was among fingerlings and young, reaching heights of 86.18 and 85.58 cm, respectively. However, the adult system did not show positive results since the growth was very low (30.45 cm) and it did not show flowering [27].

When implementing innovative systems such as aquaponics, it is important to compare them with conventional systems to check their productivity. This is why [29] evaluated the yield of sweet potato (I. batatas) in an aquaponic system with catfish versus on land.

Although sweet potato is the sixth most produced crop [30], its production has remained practically the same at 97.7 to 91.8 million metric tons in 2010 and 2019, respectively [31]. One of the limitations of production is the accumulation of viruses and mutations if the same roots/cuttings are used in later years [32]. Therefore, virus-free scions, known as "cuttings", are propagated under controlled conditions, and sold to farmers each year. For this reason, it is important to propose new systems and methods to grow sweet potatoes.

In this study, each aquaponic system contained an 1100 L fish culture unit gravity fed to a sump (350 L) where water was pumped through a sand filter and to a plant culture bed (280 L). Water overflowed from the plant culture bed into the fish culture unit.

Results showed that out of nine sweet potato cuttings, these became nine cuttings in the soil after 3 weeks, compared to 55 cuttings in the aquaponic system. Mean length, weight, and number of nodes were significantly higher ($p < 0.05$) in aquaponics, while stem diameters were similar between treatments ($p > 0.05$). Both the total phenol and the antioxidant capacity in sweet potato leaves were significantly higher in the soil. Manganese and zinc were significantly higher in leaves when grown in aquaponics, but no significant differences were detected for iron, phosphorus, or magnesium. The results show that aquaponics provides a much higher sweet potato production. The greatly improved growth of sweet potato cuttings in the aquaponic system was probably attributed, at least in part, to constant and consistent access to various nutrients originating from fish waste [29].

In this final study, hydroponic feeders planted with water spinach (*Ipomoea aquatica*) were integrated with an indoor recirculating aquaculture tank with limited water exchange to regulate water quality for intensive culture of African catfish (*Clarias gariepinus*). The main objectives of the study were: (1) to investigate the performance of water spinach in the treatment of wastewater from aquaculture with medium water flow rates, and (2) to examine the effect of flow on water quality and plant growth in the integration system [33].

The removal of nutrients such as inorganic nitrogen and phosphate is essential for aquaculture wastewater treatment to protect receiving waters from eutrophication, as well as for the possible reuse of treated water. In this study, a prototype of an aquaponics system was built at the Freshwater Hatchery Unit on the University of Malaysia Terengganu campus. The system consists of a fish culture tank, a hydroponic channel, a sump, a sand filter, and a water holding tank [34]. Three of the hydroponic troughs were stocked with water spinach (*Ipomoea aquatica*) and the other was not stocked to study the effect of plant use on water quality parameters.

Additionally, the effect of five different water flows (0.8, 1.6, 2.4, and 3.2) L/min was tested to relate nutrient removal and water quality to plant growth. Results showed that the recirculating aquaponic system removed 5-day biochemical oxygen demand (47–65%), total suspended solids (67–83%), total ammonia nitrogen (64–78%), and nitrite nitrogen (68–89%) and demonstrated a positive correlation with flow rates. All flow rates were found to be efficient in removing nutrients and maintaining water quality parameters within acceptable and safe limits for fish growth and survival [35].

Other results obtained indicate that a higher water flow supported the development of aerobic conditions in the hydroponic channel and hindered the denitrification processes. However, a low flow rate with a lower output oxygen content promoted denitrification and a higher NO_3 level. N removal was observed at lower flow rates (0.8 L/min and 1.6 L/min).

Regarding the crops, the average height of the plant at the time of harvest was in the range of 45 to 50 cm, and the yield range of 2.0 to 2.2 kg/carcass. The plant was able to significantly reduce the pollution load from aquaculture wastewater stocked with African catfish. Finally, it is important to highlight that the results of this study showed that both the growth of the plants and the production of the African catfish were better with a flow rate of 1.6 L/min.

Below, in Table 1 we can see the summary breakdown of the studies of existing sustainable systems previously evaluated and their biological indicators.

TABLE I.
Studies of existing sustainable systems and their respective biological indicators.

Country	Plants	Fish	Temperature (°C)	pH	Ammonium (mg/L)	Nitrite (mg/L)	Dissolved Oxygen (mg/L)	Nitrate (mg/L)
Mexico [17]	Cuban oregano (*Plectranthus amboinicus (Lour.) Spreng*), vaporub (*Petroselinum purpuratus Harv*) and mint (*Mentha X verticillata L*)	Tilapia (*Oreochromis niloticus x O. aureus*)	20-31.5	5.7-7.59	(2-50)	0.035-1.84	4-5.3	0.10-24.60
Mexico [27]	Tomato (*Licopersicum sculentum L.)*	Tilapia (*Oreochromis niloticus*)	23.61-31.2	7.64-8.31	0.90 ± 0.45	1.28 ± 0.99	4.1- 7.51	0.3-30
India [23]	Spinach (*Spinacia oleracea*)	Nile Tilapia (*Oreochromis Niloticus*)	28.30 ± 0.21	8.18 ± 0.10	0.17 ± 0.11	0.08 ± 0.08	5.74 ± 0.14	2.78 ± 0.29
United States of America [29]	Sweet potato (*Ipomoea batatas*)	Catfish (*Siluriformes*)	28.75 ± 0.02	7.20 ± 0.00	0.25 ± 0.03	0.05 ± 0.00	7.25 ± 0.01	10.00 ± 0.05
Malaysia [33]	Water Spinach (*Ipomoea aquatica*)	African Catfish (*Clarias gariepinus*)	27–29	7.56-7.28	2.3–3.9	0.06–0.19	-	18.77 ± 0.22

C. Electric Generation

Current systems for bioenergy production, such as bioethanol and biodiesel, still have some drawbacks. They compete with food production for arable land and fertilizer, require additional energy input, and are less "sustainable" or "green" than consumers demand [36], [37]. In the following, we propose a plant microbial fuel cell concept, which lacks these drawbacks and promises high yields.

Plants are natural absorbers of solar radiation and during photosynthesis, they produce organic matter. A large part of the organic matter produced by plants is excreted into the soil through the roots. Microorganisms that live around the roots in the soil consume this organic matter. Therefore, electrons are released as a result of this consumption. By placing an electrode near the roots, these energy-rich electrons are used as electrical energy [38].

A microbial fuel cell, known as MFC for its acronym (microbial fuel cell), also called biological fuel cell is a bioelectrochemical system. In which a current is powered by using bacteria and mimicking the bacterial interactions that naturally occur in nature. A microbial fuel cell is a device that converts chemical energy into electrical energy through the catalytic reaction of microorganisms. In general terms, MFCs are mainly classified into two types: 1) Mediating MFC. 2) MFC without a mediator [39].

1. Mediator Microbial Fuel Cell: Most microbial cells are electrochemically inactive in these systems. In this fuel cell, the mediators are responsible for the transmission of electrons from the microbial cells to the electrode. Some examples of mediators are thionine acetate, methyl viologen, methyl blue, humic acid, and neutral red. It is important to highlight that most of the mediators used in this type of MFC are expensive and also toxic substances [39].

2. Microbial fuel cell without mediators: As the name implies, here no mediators are used in the electricity generation process. They do not require a mediator as these cells use naturally occurring electrochemically active bacteria to transfer to the electrode, and these electrons are transported directly from the bacterial respiratory enzyme to the electrode. An example of a mediator-free MFC is the plant microbial fuel cell (P-MFC) [39].

The P-MFC aims to transform solar radiation into green electricity cleanly and efficiently by integrating the roots of a living plant into the anode compartment of a microbial fuel cell. It is based on two proven processes, the rhizodeposition of organic compounds by living plants and the generation of electricity from organic compounds in the microbial fuel cell. The living plant photosynthesizes in its leaves, so solar energy is used to fix carbon dioxide in the form of carbohydrates. Depending on the plant species, age, and environmental conditions, up to 60% of the net fixed carbon can be transferred from its leaves to the roots [40].

The plant root system produces and releases different types of organic compounds into the soil, including (1) exudates: sugars, and organic acids; (2) secretions: polymeric carbohydrates, and enzymes; (3) lysates: dead cell materials; and (4) gases: ethylene and CO2 [41]. The set of these release processes is called plant rhizodeposition and its products, the rhizodeposits, are used in the P-MFC as a renewable bioenergetic substrate. The rhizodeposits produced can add up to 40% of the photosynthetic productivity of the plant. Rhizosphere reservoirs contain carbon, and a part of this carbon can be used by microorganisms in the rhizosphere, which can lead to mutually beneficial interactions between plants and microorganisms.

Bacteria, for example, can positively interact with plant roots by forming protective biofilms or by producing antibiotics as biological controls against potential pathogens [41]. Since the largest fraction of rhizodeposits are small molecules, they are efficiently synthesized by the plant and efficiently metabolized by bacteria. In the P-MFC, the main idea is that plant rhizodeposits will be used as substrates by bacteria to generate electricity in the microbial fuel cell. The microbial fuel cell is an emerging technology that transforms biodegradable substrates from wastewater or (energy) crops into electricity [42], [43].

In the P-MFC system, plants and bacteria were present to convert solar energy into green electricity. The main idea can be seen in Fig. 3, where plants produce rhizodeposits, mainly in the form of carbohydrates, and bacteria convert these rhizodeposits into electrical energy via the fuel cell.

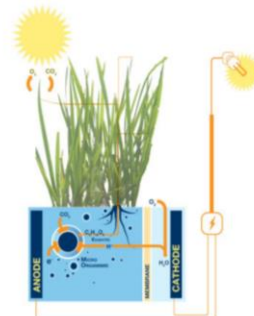

Fig. 3 Model of an electrical generation system based on a vegetable microbial fuel cell [38].

It is important to underline that not all plant species can be applied to these systems. Or rather, high-efficiency returns will not be obtained. Listed below are certain types where P-MFCs planted with these species generated comparatively high amounts of energy and produced even significant amounts of biomass that could often be harvested.

Oryza sativa (also called Asian rice) and grass have a very high power density with P-MFC technology. The list of some plants is shown in Fig. 4. The researchers found that grasses are the most promising plant species for P-MFCs, as they can overcome certain limitations of such systems and can produce high-shoot biomass during their growth. operation [39]. This biomass could also be used for other purposes, such as biogas production and also as animal feed. The prerequisites for plants are:

- Plants must be able to grow with roots completely submerged.
- Use aquatic or marsh plants.
- Use plants for indoor use when planning to put the system indoors and local species for outdoors when planning to put the system outdoors [39].

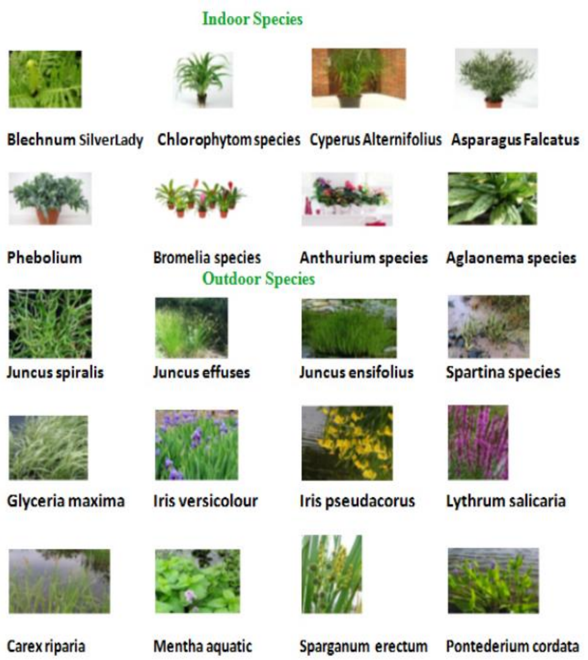

Fig. 4 List of plants to be used in P-MFC systems [39].

Managing to apply the theory, in a study carried out in The Netherlands, the experiment was carried out for 118 days and a maximum electrical energy production of 67 mW/m^2 of anode surface was achieved [38].

In this study, Great manna grass (*Glyceria maxima*), also called sweet grass, was chosen because it is one of the few species that can grow in the anaerobic sediments of riverbanks. These anaerobic conditions are necessary for the proper functioning of the anodic compartment of a P-MFC.

Here they estimate that the achievable electricity production of a P-MFC is 21GJ/ha per year. This estimate is based on solar radiation of 150 mW/m^2 in Europe, average photosynthetic efficiency of 2.5% [38], a rhizodeposition yield of 40% [40], a rhizodeposition availability for microorganisms of 30% [44], a microbial fuel cell energy recovery of 29% [45], and a 6-month growing season.

With this proposed system it is possible to produce green electricity through the non-destructive collection of rhizodeposits from the plant. This has important environmental advantages, such as the absence of transport of harvested biomass, the conservation of nutrients in the ecosystem, the use of a renewable energy source, and the absence of combustion or additional greenhouse gas emissions during production [38].

In addition, from the social point of view, the P-MFC has advantages. It can be implemented in natural environments such as wetlands with minimal disturbance to the landscape and without being competitive with agricultural land needed for food. Therefore, in the future, wetlands and also salty soils could be transformed worldwide into green power plants that generate electricity in a carbon-neutral way.

Additionally, there is another incentive to wire the fields in this way, since according to [46], the technology could significantly contribute to the fight against global warming. The anaerobic conditions that are suited to plants like rice and sugarcane are also prime environments for a class of bacteria that break down organic matter and release electrons that then generate methane, a potent greenhouse gas. Placing an anode in the ground provides an alternate path for these electrons and, if efficient enough to collect them, this should reduce methane generation [47]. With rice paddies contributing up to 20% of the world's methane emissions, reducing this and producing modest amounts of electricity represents another advantage of these systems.

Below, Table 2 breaks down various applied studies comparing their yields and the maximum electrical generation obtained.

TABLE II.
Comparison of existing studies evaluating their yields and the maximum electrical generation obtained.

Plant	Electrode Material		Electrical Generation (mW/m^2)	Time of Operation (days)	Internal Resistance (Ω)	Catalyst	Energy Conversion Efficiency (%)	Reference
	Anode	Cathode						
Glyceria maxima	Graphite granules	Graphite felt	67	67	525	O2	0.01	[36]
Oryza sativa ssp. indica		Graphite granules	33	134	-	Ferricyanide	0.004	[37]
Spartina anglica		Graphite felt	79	78	1800	O2	0.01	[38]
S. anglica			100	33	750	Ferricyanide	0.01	[38]
Arundinella anomala	Graphite rod in graphite grains		22	112	-	O2 or Ferricyanide	0.001	[39]
S. anglica			222	154	-	O2 or Ferricyanide	0.001	[39]
O. sativa ssp. indica	Graphite granules	Graphite granules	-	175	-	Ferricyanide or O2 (bacteria)	-	[40]
Oryza sativa L. cv. Sasanishiki	Graphite felt	Graphite felt	120	120	156	O2	-	[41]

Oryza sativa L. cv. Satojiman	-	-	-	-	-	O2	-	[42]
Echinorriea crassipes	Graphite discs	Graphite discs	80.08	210	-	-	-	[43]
G. maxima	Graphite granules	Graphite granules	32	225	-	-	-	[44]
Typha latifolia	Carbon felt	Carbon felt	6.12	74	820	-	-	[45]

D. Proposing a preliminary system.

After observing the qualities of both systems previously mentioned, the possibility of merging them arose, considering the energetic benefits. The proposed design can be observed in Fig. 5. Depicting a diagram of a P-MFC system powering up both the pump and timer of our aquaponic system.

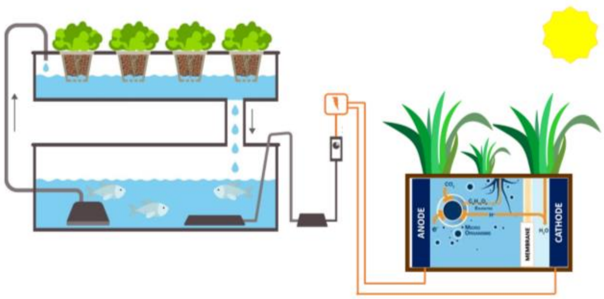

Fig. 5 Diagram of the proposed system, adapted from [38],[46].

Analyzing the different plants from Table 2, those grown in Panama include several species of rice (e.g., *Oryza sativa*) [47]. This plant could be an excellent choice because unlike the others it can be harvested and bring nutritional value to the occupants, adding another source of sustainable food generation.

Moreover, the aquaponic system may use Tilapia *(Oreochromis niloticus*), a specie we can find locally, and harvest Spinach (*Spinacia oleracea*). The biological parameters such as those displayed in [23] need to be regulated. As shown in [23], this arrangement comes with the benefit of using salt water. Fish and crustacean aquaculture using inland saline groundwater opens a new route to convert underutilized saline groundwater into productive resources, which helps immensely in the context of freshwater scarcity [22].

IV. Conclusions

Due to the populational growth and the scarcity of arable land and freshwater; evaluating a biotechnological system for electricity generation that allows sustainable local cultivation is of the utmost importance. For this, a systematic review of various biomimetic alternatives was carried out. Seeking to follow the principles of biomimicry, eco-design, and circular economy.

In this paper, we did a systematic review, following a bibliometric analysis based on two main aspects, sustainable crops, and bioinspired energy generation. Employing the software VOSviewer, a map was created through a keyword co-occurrence analysis using the full counting method. Where we could visualize the research trends regarding energy and food generation. This method gives a better perspective into the occurrence of different terms to observe which way research is heading and what priorities are present.

After the bibliometric review of existing aquaponic systems, we could see how tilapia and catfish are the most present fish employed. Regarding plants, research showed from tomatoes, spinach, mint, sweet potato, and oregano were the most predominant. The biological parameters needed to optimize these systems were also evaluated.

Regarding bio-inspired energy generation, the P-MFC represents an interesting and innovative proposition. Where energy can come from sustainable food harvesting. For our design, we chose *Oryza sativa* for our P-MFC system, because it can be obtained locally and has a high survival rate. Additionally, it is a common ingredient in Panamanian diets. Regarding the aquaponic system, tilapia and spinach were selected, also due to their adaptability to the tropical weather in Panama and their local presence. It is important to highlight that for our aquaponic system, freshwater will not be employed. Seeing as how both species adapt well to saline water and thus helps regarding the context of freshwater scarcity.

On account of the different benefits mentioned above, we consider our proposed design to be an innovative solution to many current problems. This study remains as evidence of the relevance of food and energy generation alternatives. Focusing on bio-inspired and sustainable technologies.

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References

[1] M. S. Al-Homoud, "Computer-aided building energy analysis techniques," 2001. [Online]. Available: www.elsevier.com/locate/buildenv

[2] International Energy Agency., *World Energy Outlook 2015.* OECD, 2015.

[3] H. R. M. Roser, "Urbanization - Our World in Data," 2018. https://ourworldindata.org/urbanization#what-share-of-people-will-live-in-urban-areas-in-the-future (accessed Mar. 28, 2022).

[4] D. Ürge-Vorsatz, L. F. Cabeza, S. Serrano, C. Barreneche, and K. Petrichenko, "Heating and cooling energy trends and drivers in buildings," *Renewable and Sustainable Energy Reviews*, vol. 41. Elsevier Ltd, pp. 85–98, 2015. doi: 10.1016/j.rser.2014.08.039.
[5] K. Sudhakar, M. Winderla, and S. S. Priya, "Net-zero building designs in hot and humid climates: A state-of-art," *Case Stud. Therm. Eng.*, vol. 13, Mar. 2019, doi: 10.1016/j.csite.2019.100400.
[6] The World Bank, "Panama: Development news, research, data | World Bank," 2021. https://www.worldbank.org/en/country/panama (accessed Mar. 28, 2022).
[7] G. Oficial, "Gaceta Oficial Digital," 2016.
[8] World Health Organization, "World Health Organization Nutrition for Health and Development (NHD) Sustainable Development and Healthy Environments (SDE) for Health and Development," 2000.
[9] Food and Agriculture Organization of the United Nations., *The state of food insecurity in the world, 2010 : addressing food insecurity in protracted crises.* Food and Agriculture Organization of the United Nations, 2010.
[10] F. Chávez, "Evaluación de un sistema experimental de acuaponia • Evaluation of an experimental aquaponic system," 2005.
[11] S. Diver, "IS A PROJECT OF THE NATIONAL CENTER FOR APPROPRIATE TECHNOLOGY," 2000. [Online]. Available: www.attra.ncat.org
[12] R. Martínez-Yanéz, "Acuaponía: ¿Una posibilidad para tener en casa?," 2013. [Online]. Available: http://www.redicinaysa.ugto.mx/,
[13] P. V Nelson, D. C. Sanders, L. Hodges, and M. R. McMurtry, "Sand culture of vegetables using recirculated aquacultural effluents," *Appl. Agric. Res.*, vol. 5, no. 4, pp. 280–284, 1990.
[14] E. S. Rakocy, J. E., Bailey, D. S., Shultz, R. C., & Thoman, "Update on tilapia and vegetable production in the UVI aquaponic system. New dimensions on farmed tilapia," *Proc. from 6th Int. Symp. Tilapia Aquac.*, vol. 000, pp. 1–15, 2004.
[15] N. Savidov, "Evaluation and Development of Aquaponics Production and Product Market Capabilities in Alberta. Phase II.," 2005.
[16] A. Graber and R. Junge, "Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production," *Desalination*, vol. 246, no. 1–3, pp. 147–156, 2009, doi: 10.1016/j.desal.2008.03.048.
[17] R. Campos, A. López, D. A. Avalos, A. Asiain, and J. L. Reta, "Caracterización fisicoquímica de un efluente salobre de tilapia en acuaponia," *Rev. Mex. Ciencias Agrícolas*, vol. 5, pp. 939–950, 2013.
[18] A. S. El Mahmoudi, K. M. Al-barrak, and M. A. Massoud, "2-D Electrical Tomography for Mapping of Aquifers at the New Campus of King Faisl University , Al Hassa , KSA," vol. 1, no. 6, pp. 397–410, 2011.
[19] A. K. Verma, S. K. Gupta, and R. K. Isaac, "Calibration and Validation of SWAP to Simulate Conjunctive Use of Fresh and Saline Irrigation Waters in Semi-Arid Regions," *Environ. Model. Assess.*, vol. 19, no. 1, pp. 45–55, 2014, doi: 10.1007/s10666-013-9379-x.
[20] V. Re and E. Sacchi, "Tackling the salinity-pollution nexus in coastal aquifers from arid regions using nitrate and boron isotopes," *Environ. Sci. Pollut. Res.*, vol. 24, no. 15, pp. 13247–13261, 2017, doi: 10.1007/s11356-017-8384-z.
[21] A. K. Verma, S. K. Gupta, and R. K. Isaac, "Long-term Cyclic Irrigation in Subsurface Drained Lands: Simulation Studies with SWAP," *J. Agric. Sci.*, vol. 5, no. 1, 2012, doi: 10.5539/jas.v5n1p84.
[22] A. Kumar, V. Harikrishna, A. K. Reddy, N. K. Chadha, and A. M. B. Rani, "Salinity tolerance of Pangasianodon hypophthalmus in inland saline water: Effect on growth, survival, and hematological parameters," *Ecol. Environ. Conserv.*, vol. 23, no. 1, pp. 567–574, 2017.
[23] R. M. Thomas, A. K. Verma, H. Krishna, S. Prakash, A. Kumar, and R. M. Peter, "Effect of salinity on growth of Nile tilapia (Oreochromis niloticus) and spinach (Spinacia oleracea) in the aquaponic system using inland saline groundwater," *Aquac. Res.*, vol. 52, no. 12, pp. 6288–6298, 2021, doi: 10.1111/are.15492.
[24] S. J. Coughlan and R. G. W. Jones, "Some responses of Spinacea oleracea to salt stress," *J. Exp. Bot.*, vol. 31, no. 4, pp. 97–123, 1980, doi: 10.1093/jxb/31.4.883-a.
[25] P. M. Hasegawa and R. A. Bressan, "Plant Cellular and Molecular Responses to High Salinity," 2000.
[26] B. Jacoby, *Handbook of plants*. 2011. doi: 10.5962/bhl.title.26210.
[27] L. Félix-Cuencas, J. F. García-Trejo, S. López-Tejeida, J. J. de León-Ramírez, and G. M. Soto-Zarazúa, "Effect of three productive stages of tilapia (Oreochromis niloticus) under hyper-intensive recirculation aquaculture system on the growth of tomato (Solanum lycopersicum)," *Lat. Am. J. Aquat. Res.*, vol. 49, no. 5, pp. 689–701, 2021, doi: 10.3856/vol49-issue5-fulltext-2620.
[28] B. Bugbee, "Nutrient management in recirculating hydroponic culture," *Acta Hortic.*, vol. 648, no. June, pp. 99–112, 2004, doi: 10.17660/ActaHortic.2004.648.12.
[29] N. Romano, S. Francis, S. Islam, A. Powell, and H. Fischer, "Aquaponics substantially improved sweet potato (Ipomoea batatas) slip production compared to the soil but decreased phenol and antioxidant capacity," *Aquac. Int.*, no. July 2022, doi: 10.1007/s10499-022-00923-6.
[30] CIP, "Sweetpotato Facts and Figures - International Potato Center," 2021. https://cipotato.org/sweetpotato/sweetpotato-facts-and-figures/ (accessed Sep. 25, 2022).
[31] Statista, "Sweet potato production worldwide 2020," 2020. https://www.statista.com/statistics/812343/global-sweet-potato-production/ (accessed Sep. 25, 2022).
[32] C. A. Clark, R. A. Valverde, S. Fuentes, L. F. Salazar, and J. W. Moyer, "Research for improved management of sweetpotato pests and diseases: Cultivar decline," *Acta Hortic.*, vol. 583, pp. 103–112, 2002, doi: 10.17660/ActaHortic.2002.583.11.
[33] A. Endut, A. Jusoh, N. Ali, W. N. S. Wan Nik, and A. Hassan, "Effect of flow rate on water quality parameters and plant growth of water spinach (Ipomoea aquatica) in an aquaponic recirculating system," *Desalin. Water Treat.*, vol. 5, no. 1–3, pp. 19–28, 2009, doi: 10.5004/dwt.2009.559.
[34] P. D. Hiley, "The reality of sewage treatment using wetlands," *Water Sci. Technol.*, vol. 32, no. 3, pp. 329–338, 1995, doi: 10.1016/0273-1223(95)00633-8.
[35] M. G. Poxton and S. B. Allouse, "Water quality criteria for marine fisheries," *Aquac. Eng.*, vol. 1, no. 3, pp. 153–191, 1982, doi: 10.1016/0144-8609(82)90026-7.
[36] C. J. N. B. Strik, David P. B. T. B., H. V. M. Hamelers (Bert), Jan F. H. Snel, "Green electricity production with living plants and bacteria in a fuel cell," *Arch. Thermodyn.*, vol. 32, no. 9, pp. 870–876, 2008, doi: 10.1002/er.1397.
[37] L. De Schamphelaire *et al.*, "Microbial fuel cells generating electricity from rhizodeposits of rice plants," *Environ. Sci. Technol.*, vol. 42, no. 8, pp. 3053–3058, 2008, doi:

10.1021/es071938w.
[38] R. A. Timmers, D. P. B. T. B. Strik, H. V. M. Hamelers, and C. J. N. Buisman, “Long-term performance of a plant microbial fuel cell with Spartina anglica,” *Appl. Microbiol. Biotechnol.*, vol. 86, no. 3, pp. 973–981, 2010, doi: 10.1007/s00253-010-2440-7.
[39] M. Helder, D. P. B. T. B. Strik, H. V. M. Hamelers, A. J. Kuhn, C. Blok, and C. J. N. Buisman, “Concurrent bio-electricity and biomass production in three Plant-Microbial Fuel Cells using Spartina anglica, Arundinella anomala, and Arundo donax,” *Bioresour. Technol.*, vol. 101, no. 10, pp. 3541–3547, 2010, doi: 10.1016/j.biortech.2009.12.124.
[40] L. De Schamphelaire, A. Cabezas, M. Marzorati, M. W. Friedrich, N. Boon, and W. Verstraete, “Microbial community analysis of anodes from sediment microbial fuel cells powered by rhizodeposits of living rice plants,” *Appl. Environ. Microbiol.*, vol. 76, no. 6, pp. 2002–2008, 2010, doi: 10.1128/AEM.02432-09.
[41] N. Kaku, N. Yonezawa, Y. Kodama, and K. Watanabe, “Plant/microbe cooperation for electricity generation in a rice paddy field,” *Appl. Microbiol. Biotechnol.*, vol. 79, no. 1, pp. 43–49, 2008, doi: 10.1007/s00253-008-1410-9.
[42] K. Takanezawa, K. Nishio, S. Kato, K. Hashimoto, and K. Watanabe, “Factors affecting electric output from rice-paddy microbial fuel cells,” *Biosci. Biotechnol. Biochem.*, vol. 74, no. 6, pp. 1271–1273, 2010, doi: 10.1271/bbb.90852.
[43] S. Venkata Mohan, G. Mohanakrishna, and P. Chiranjeevi, “Sustainable power generation from floating macrophytes based ecological microenvironment through embedded fuel cells along with simultaneous wastewater treatment,” *Bioresour. Technol.*, vol. 102, no. 14, pp. 7036–7042, 2011, doi: 10.1016/j.biortech.2011.04.033.
[44] R. A. Timmers *et al.*, “Microbial community structure elucidates performance of Glyceria maxima plant microbial fuel cell,” *Appl. Microbiol. Biotechnol.*, vol. 94, no. 2, pp. 537–548, 2012, doi: 10.1007/s00253-012-3894-6.
[45] Y. L. Oon *et al.*, “Hybrid system up-flow constructed wetland integrated with microbial fuel cell for simultaneous wastewater treatment and electricity generation,” *Bioresour. Technol.*, vol. 186, pp. 270–275, 2015, doi: 10.1016/j.biortech.2015.03.014.
[46] GreenKit, “A Complete Guide to Aquaponics for Beginners,” 2023. https://www.greenkit.net/aquaponics-for-beginners/ (accessed Feb. 01, 2023).
[47] N. Torres, R. Rakwal, and H. Iwahashi, “Efecto ambiental del ozono sobre la especie panameña de arroz (Oryza sativa cv. PANAMA 1048, PANAMA 1537, PANAMA 4721, PANAMA 3621),” no. August, 2007.