

## Article

# Integrated Aquaculture Recirculation System (IARS) Supported by Solar Energy as a Circular Economy Alternative for Resilient Communities in Arid/Semi-Arid Zones in Southern South America: A Case Study in the Camarones Town

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**Abstract:** In this work, the cultivation of river shrimp was implemented through intensive use of solar radiation for the sustainable development of the Camarones, a village in Chile. An aquaculture production plant was built under water recirculation to produce 8000 kg of river shrimp and rainbow trout per year, in a 25:75 ratio, respectively. This was developed taking into account (1) the concept of how to help resilient communities, considering the principles of the circular economy; (2) that the cultivation of these species will use solar water treatment technology to reduce arsenic content present in the natural waters of the Camarones River; and (3) how to add value to the residues obtained from the production plant for better agriculture and to have water to preserve the ecosystem. In addition, this initiative will rely on solar energy and radiation to produce electrical energy and a photochemical reaction to remove arsenic from the water. This work complies with 10 of the 11 principles of the Circular Economy, making it a potential alternative for all areas of the world that have similar characteristics.

**Keywords:** integrated aquaculture recirculation system; solar water treatment; circular economy; photovoltaic energy

## 1. Introduction

Water is an essential element for energy, food production, socioeconomic development, and the ecosystem. However, water scarcity affects 40% of people globally, and 80% of wastewater returns to the ecosystem without being treated or reused [1].

In 2019, there were 135 million people without access to sufficient food. Unfortunately, as a result of Coronavirus Disease 2019 (COVID-19), it is expected that around 265 million people could face starvation by the end of 2020 [2]. In this sense, there is a great challenge to provide food and livelihoods

to a world population that, by the year 2050, will exceed 9 billion people [3]. Furthermore, 100% access to adequate food will be required in developing countries [4]. From 2003 to date a great increase in food prices has been observed; it is believed that this is being caused by climate change, an increase in oil prices, and financial market speculation [3,5].

Moreover, as a result of the changes in the use of land, habitat fragmentation, overexploitation, illegal trade in wild species, pollution, and climate change, humanity is heading to a massive extinction of species, which compromises the ecological integrity of the land and its ability to meet human needs [6]. According to a 2010 United Nations (UN) report, capture fisheries from the world's oceans has likely reached its maximum potential [7], affecting more than 500 million people in the world [8]. It is necessary to point out that fish is an essential source of food for 3 billion people globally, constituting at least 50% of the animal proteins and essential minerals consumed by 400 million people in the poorest countries [8,9]. In this context, according to the UN Food and Agriculture Organization (FAO), in 2018 the global aquaculture production of food fish was 80 million tons, and sales corresponded to USD \$231.6 billion, providing 10.8 kg of fish per capita in 2016. It should be noted that fish pond farming in freshwater plays an important role in aquaculture production, 47.5 million tons of fish were reached in 2016 [10].

Considering that sustainable development cannot be achieved without resilient livelihoods [3], we chose, as an example of resilience, Camarones, a village in the Arica and Parinacota Region in the northern part of Chile. This town has an interior desert climate, is over 1000 m above sea level, without coastal oceanic influence. In addition, the Camarones Valley is characterized by being arid, with a nil annual rainfall, and with average temperatures of 18 °C. Moreover, the days are mostly filled with clear skies, and drier than the coastal desert climate, with an average relative humidity of 50% [11].

In this town, through an initiative of the Chilean Solar Research Center [12], a pilot-scale system driven with solar energy for river shrimp (*Cryphiops caementarius*) farming, using solar water treatment technology, was implemented, in order to reduce the arsenic content in the natural waters of the Camarones River. It is necessary to point out that water contamination caused by arsenic is a health issue of great importance at the global level, there are studies that indicate that countries, such as the United States, Chile, Mexico, Bolivia, Perú, Cambodia, China, Vietnam, Bangladesh, Bengal, Thailand, Nepal, and Ghana have dangerous levels of this metalloid. It has carcinogenic and neurotoxic effect in humans. Arsenic is distributed in the earth's crust, with an average concentration of 2 mg kg<sup>-1</sup>, and is present in all types of rocks, soil, water, and air. This element can cause chronic hydroarsenicism in people; it is classified as carcinogenic to humans (Group 1, according to the International Agency for Research on Cancer [13]. In this sense, taking into account all of the different parts of the problem, in order to implement the solution, a circular economy concept is considered in order to ensure sustainability.

## 2. Implementation

To implement IARS, a description of place was first performed; then, an integrated aquaculture recirculation system, supported by a solar energy system is described. Finally, the circular economy is discussed.

### 2.1. The Camarones Area

Camarones Valley is a village in the Arica and Parinacota Region, Chile, in southern South America, according to geo referencing 7897802.821 North–409758.221 East, Datum World Geodetic System 1984 (WGS 84) (See Figure 1). This town has an interior desert climate; it is located in the pampas, is over 1000 m above sea level, without coastal oceanic influence. In addition, the Camarones Valley is characterized by being very arid, with almost zero annual rainfall, and with average temperatures that reach 18 °C. Moreover, the days are mostly filled with clear skies and luminosity. It is drier than the coastal desert climate, with an average relative humidity of 50% [11]. On the other hand, this valley is crossed by the Camarones River, immersed in the basin of the same name; it has an area of 4767 km<sup>2</sup> with a length of 135 km. It is formed by the confluence of the Ajatama and Caritaya

ivers, in the Arepunra sector, in the Andes mountain range, at an altitude of 2900 m above sea level. Both tributaries have volcanic influence, from the Chuquicamata (5590 m) and Anocaire (5050 m) volcanoes [14]. In addition, its waters are characterized by having elements and compounds at high concentration, such as total dissolved solids, arsenic, and boron, whose quantities are 1500 mg L<sup>-1</sup> [15], 1 mg L<sup>-1</sup>, and 10 mg L<sup>-1</sup> [16], respectively.



**Figure 1.** Geographical location of the Camarones area and photographic image of the river of the same name.

In relation to the quality of its soils the Camarones town, it has a sandy loam texture, and high salinity but poor permeability (being limiting for crops). This phenomenon is due to the poor quality of Camarones River and, according to the physical–chemical characterization of its waters [17,18], parameters, such as arsenic, exceed Chilean regulations for both drinkable water (Norma Chilena NCh409/1 of 2005) [19] and irrigation (Norma Chilena NCh1333 of 1978 Modificada 1987) [20], by 100 and 10 times, respectively, as it is seen in Table 1).

**Table 1.** Characterization of Camarones River water [17,18].

Physical–Chemical Parameters	Unit	Camarones River Water Values	NCh409/1 of 2005 Potable Water	NCh1333 of 1978 Modificada 1987 Irrigation Water
pH	-	8.3	6.5–8.5	6.0–9.0
Electrical conductivity	µs cm <sup>-1</sup>	2200	-	-
Temperature	°C	22.30	-	30.00
Chloride	mg L <sup>-1</sup>	564.30	400.00	200.00
Sulfate	mg L <sup>-1</sup>	178.50	500.00	250.00
Sodium	mg L <sup>-1</sup>	557.70	-	-
Potassium	mg L <sup>-1</sup>	34.20	-	-
Manganese	mg L <sup>-1</sup>	0.10	0.10	0.20
Magnesium	mg L <sup>-1</sup>	15.60	125.00	-
Calcium	mg L <sup>-1</sup>	101.80	-	-
Arsenic	mg L <sup>-1</sup>	1.20	0.01	0.10
Total dissolved solids	mg L <sup>-1</sup>	1561	1500	-

It is necessary to emphasize that, due to the quality of the water of the Camarones River, it is essential to treat its waters to eliminate arsenic [21,22].

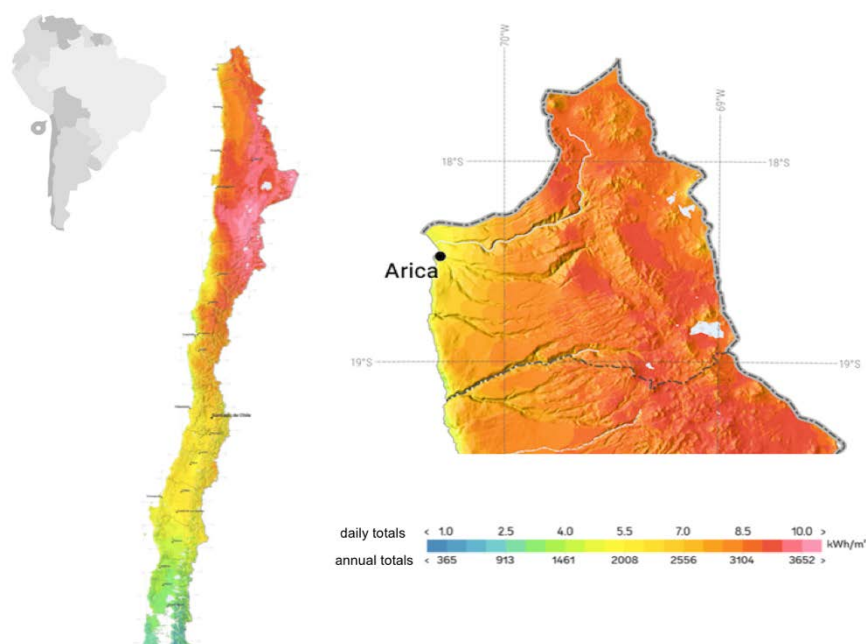
The main problem that affects the commune of Camarones is one of the localities with the highest isolation condition in Chile, which implies the low habitability of this rural area, with a population of 1255 inhabitants [23]. This problem affects their socioeconomic development, mainly associated with the low availability of basic services, due to the poor quality of natural water and the lack of electricity that fully supports the requirements of the village. These characteristics have been limiting over time, causing, in the Camarones community, a lack of diversity of its agricultural products, being its main crop alfalfa for animal (sheep and cow) consumption, and the production of meat, milk, and cheese [24].

On the other hand, as indicated by the United Nations World Water Assessment Program [22], the goal is for human settlements to be inclusive, safe, resilient, and sustainable. Thus, the construction of resilient infrastructure in the Camarones commune is an opportunity to improve the quality of life for its inhabitants. For this, the construction and start-up of an integrated aquaculture recirculation system in the commune is considered an alternative instrument for development. This system is characterized by the use of solar radiation and photovoltaic energy in its components. In addition, it is considered a profitable, scalable, and replicable business model, which will help promote the economic development of Camarones in a sustainable way, through the cultivation of two species: river shrimp (*Cryphiops caementarius*) and trout (*Oncorhynchus mykiss*).

## 2.2. Solar Radiation

The greatest potential of the Camarones area is an average solar radiation of 2957 kWh m<sup>2</sup> year<sup>2</sup> [25,26] (Figure 2), which represents an opportunity to use solar energy for different applications, such as photovoltaic, thermo solar technologies, and solar water treatment, among other things.

Thus, it is expected to promote and implement aquaculture of river shrimp and rainbow trout, through technologies based on the use of solar resources to improve the quality of the natural waters of Camarones, and to be used for farming these species, as well as to produce electrical energy through photovoltaic panels for the Integrated Aquaculture Recirculation System (IARS) operation.



**Figure 2.** Solar resource map, normal direct irradiation in the Arica and Parinacota Region (source: Solargis, 2019) [26].

## 2.3. Water Quality in Hydrobiological Species Crops

Water quality is one of the most important factors when considering intensive fish farming, since a series of factors that condition both productivity and the appearance and development of pathological processes, whether infectious or toxicological, depend on it [27]. A better understanding of the relationships between aquatic productivity and water quality is essential to ensure continuity in the growth of aquaculture [28]. Water quality in modern production systems has a direct impact on the health and growth of farmed species and, thus, plays a role in the development of production systems.

The construction of intensive farming systems requires complex infrastructure and investors are forced to maximize biomass production per unit volume to maintain economic viability. Because of

this, fish farmers tend to use densities above the limit, with increasing population density, water quality declines, and tends to fluctuate dramatically within the system [27].

Water quality, in its broadest sense, includes all physical, chemical, and biological characteristics [29], and in the case of industrial rainbow trout [30] and shrimp farming, this concept cannot be restricted. However, until now, water quality has usually been considered as a limited set of parameters, such as temperature, dissolved oxygen, salinity, alkalinity, hardness, ammonia, nitrites, and others. However, nowadays, given the extent of pollution of the aquatic environment and the risk of certain contaminants, the ubiquity of organic micropollutants and heavy metals make these factors to be considered. The reduction in immunocompetence may be associated with the stress response produced by exposure to chemicals. However, other contaminants, such as arsenic, copper, ammonia, or hexachlorobenzene have mechanisms of immunotoxicity independent of the stress produced by exposure [31]. The risk arising from the presence of contaminants lies not only in their toxicity to fish, but also in their influence on the human consumer.

Compared to land-based crops and animal production, fish are quite sensitive to water contaminants; therefore, aquaculture production is vulnerable to deterioration in water quality. In addition, the widespread use of chemicals has had a large and damaging impact on ecosystems and the environment. It has been hypothesized that chronic exposure to high concentrations of unionized ammonia would negatively affect fish welfare [32]. Currently, recurrent diseases in aquaculture and climatic effects have brought attention to the aquaculture industry, to implement land-based aquaculture recirculation systems as an alternative to traditional open pond and cage culture systems [33,34].

In the aquaculture recirculation system, fish feed is virtually the only source of carbon and nitrogen solids, which are the main sources of pollution. It is estimated that, by weight, the amount of solids produced in an aquaculture recirculation system represents approximately 30–60% of the applied fish feed [35]. Fish feed contains 25–65% protein [36], as does shrimp feed, corresponding to 4.1–10.7% organic nitrogen. Only about 20–30% of the nitrogen in the applied feed is retained by the fish [37,38], while the rest is excreted in the water. Therefore, it is estimated that approximately 75% of the protein nitrogen from fish is released into the water, with a significant portion composed of total ammonia nitrogen [39]. Ammonia is toxic to many fish, even at low concentrations [39,40].

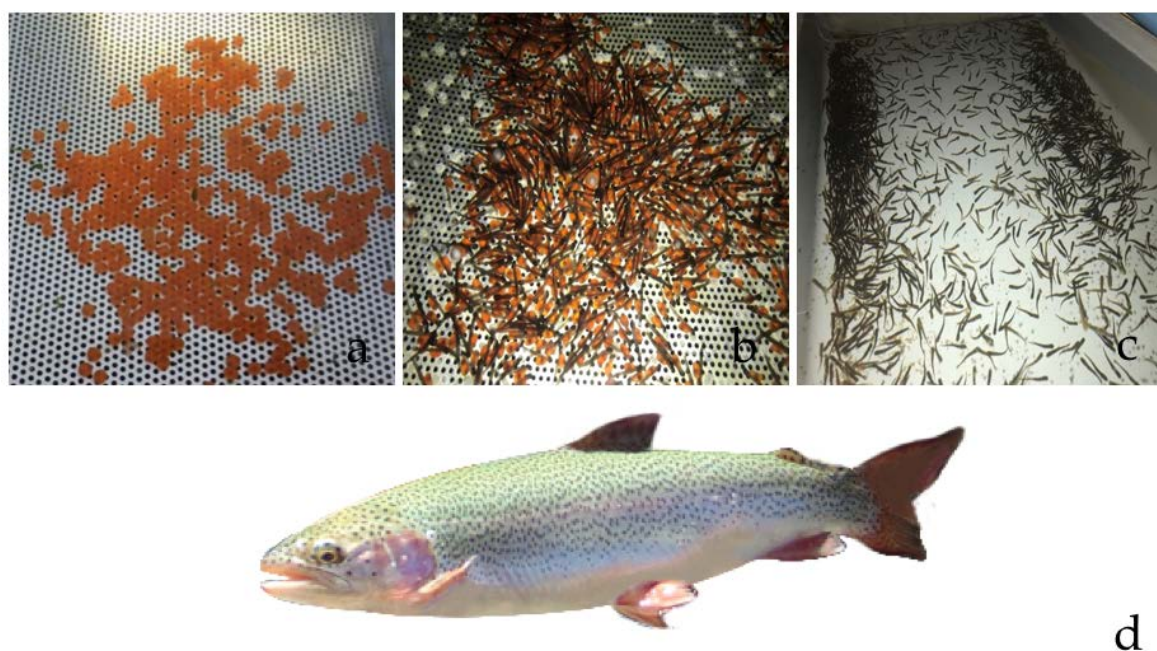
## 2.4. Farmer Species

### 2.4.1. Rainbow Trout

Rainbow trout, or *Oncorhynchus mykiss* [41], it belongs to *Salmonidae* family, genus *Oncorhynchus*, an ichthy species native to the North American Pacific coasts; due to its easy adaptation to captivity, its breeding has been widely disseminated almost all over the world [29]. Its farming in Chile started in 1974; however, it had been previously introduced for repopulation purposes in the north of the country. It is distributed in the Laguna del Inca, Lautaro, in rivers and lakes from Coquimbo to the south of Tierra del Fuego, with an isolated presence in the Andean part of the Loa River and Lake Chungará [41].

This is a resistant, fast-growing fish, easy to spawn, tolerant to a wide range of environments and manipulations, of soft meat, and highly versatile [42]. It does not reproduce naturally in farming systems; therefore, juveniles must be obtained by artificial spawning in a hatchery or by collecting eggs from wild populations. The larvae are well developed at the time of hatching (Figure 3) [43].





**Figure 3.** (a) Eggs, (b) larvae, (c) juveniles of *Oncorhynchus mykiss*, and (d) adult specimen, (photographs: own source).

#### 2.4.2. Optimal Parameters for Trout Farming

The quality of water for rainbow trout farming is given by the set of physical, chemical, and biological properties, as seen below, several parameters were taken into account:

**Temperature:** rainbow trout, such as all fish, do not have their own capacity to regulate their body temperature, since they are totally dependent on the aquatic environment in which they live. Trout, in natural conditions, is a fish that can live in waters between 0 and 25 °C, nevertheless, in our case, the growth corresponds with the range of 9 °C to 17 °C (Table 2).

**Dissolved oxygen:** the oxygen dissolved in the water is, for trout, as well as for all aquatic beings, an essential element for life. With figures inferior to 5 to 5.5 mg L<sup>-1</sup> of oxygen, trout has a great difficulty to extract, so to speak, the oxygen of the water and transport it through the gills to the sanguineous torrent [44] (Table 2).

**Nitrogenated compounds:** ammonia and nitrites are toxic and are also the main products of metabolism excretion in trout. Nitrates have low toxicity for fish, but in anaerobic or oxygen-poor situations, they can produce a denitrification process and give rise to nitrites (Table 2).

**Parasites, bacteria, and viruses:** the biological properties of water are understood to be the capacity of the water to develop a more or less abundant flora and fauna. The presence and richness of microfauna of incidence in the salmonids, is conditioned to the temperature of the water and to the organic contamination, although its presence or absence is also favored by other factors. Thus, the life cycle of some salmonid parasites can be influenced by the pH value of 7.2–8.7.

Some of the main physical and chemical properties that a body of water must fulfill for trout farming are shown in the following Table 2.

In addition, it is worth it to mention that the monitoring of water quality parameters of the trout production was optimized in a previous work of the *Fondo de Innovación para la Competitividad Regional FIC R-Project, BIP Code 30158872-0*, (Table 3).

**Table 2.** Physical and chemical properties of water for rainbow trout farming [45].

Parameter	Optimal Range	Parameter	Optimal Range
Temperature	9–17 °C	Nitrites	Not greater than 0.05 mg L <sup>-1</sup>
Dissolved oxygen	5.50–9.00 mg L <sup>-1</sup>	Ammonium Nitrogen	Not greater than 0.01 mg L <sup>-1</sup>
pH	6.5–8.5	Phosphates	Greater than 500.00 mg L <sup>-1</sup>
CO <sub>2</sub>	Less than 7.00 mg L <sup>-1</sup>	Sulfates	Greater than 45.00 mg L <sup>-1</sup>
Alkalinity	20.00–200.00 mg L <sup>-1</sup> CaCO <sub>3</sub>	Iron	Less than 0.10 mg L <sup>-1</sup>
Hardness	60.00–300.00 mg L <sup>-1</sup> CaCO <sub>3</sub>	Copper	Less than 0.05 mg L <sup>-1</sup>
NH <sub>3</sub>	Not greater than 0.02 mg L <sup>-1</sup>	Lead	0.03 mg L <sup>-1</sup>
H <sub>2</sub> S	Maximum accepted 0.002 mg L <sup>-1</sup>	Mercury	0.05 mg L <sup>-1</sup>
Nitrates	Not greater than 100.00 mg L <sup>-1</sup>		

**Table 3.** Physical and chemical properties of water for aquaculture recirculation system for rainbow trout [45].

	Ammonium mg L <sup>-1</sup>		Nitrate mg L <sup>-1</sup>		pH		Oxygen mg L <sup>-1</sup>		Temperature °C	
	Input	Exit	Input	Exit	Input	Exit	Input	Exit	Input	Exit
Month 1	0.08	0.21	0.31	0.38	6.8	6.9	5.8	5.5	14.8	15.3
Month 2	0.07	0.14	0.60	0.80	6.9	6.9	5.7	5.7	15.3	15.8
Month 3	0.16	0.19	0.36	0.36	6.9	7.0	5.6	5.5	16.7	17.9
Month 4	0.08	0.19	0.38	0.09	6.9	7.0	5.8	5.6	17.5	18.3
Month 5	0.11	0.31	0.44	0.09	7.0	6.9	6.3	6.2	17.1	17.8
Month 6	0.08	0.21	0.31	0.38	6.8	6.9	6.4	6.0	16.1	16.6
Month 7	0.07	0.14	0.60	0.80	6.9	7.0	6.3	6.0	14.7	14.9
Month 8	0.16	0.19	0.36	0.36	7.0	7.1	6.2	6.0	12.5	12.8

Another parameter to consider is the feeding, which must be palatable and contain all of the necessary elements to ensure optimal quality of the meat of the specimens, being the proteins (which must contain at least 10 essential amino acids) and the essential fatty acids indispensable for the construction of tissues and energy for the fish.

#### 2.4.3. River Shrimp

River shrimp, scientific name *Cryphiops caementarius* (Molina, 1782), belongs to the family *Palaemonidae*, genus *Cryphiops*; it is distributed in the rivers of western coasts of Peru and Chile. In Chile, it is present in the area from the XV region of Arica and Parinacota to Valparaíso (Maipo River). It inhabits rivers of variable flow, typical in the northern part of Chile. The shrimp is robust, has a long and thick abdomen like the cephalothorax, a rostrum with a dorsal crest adorned by a row of 6 to 7 thick teeth, and its size range varies between 15 mm of cephalothorax up to 72 mm [46].

The river shrimp live in rocky bottom sectors, remaining, during the day, hidden among the coastal vegetation, submerged or under rocks at the bottom of the river, and their activity is preferably nocturnal. The highest concentration of larvae is found in the river mouths, this is due to a positive affinity to salinity; later they go higher upstream of the river. Thus, in rivers, an inversely proportional relationship is detected between height and number of individuals; that is, the higher the height, the lower the abundance of shrimp. However, at higher altitudes, larger sizes are observed [47].

This species is threatened by the introduction of trout that feed on it and also by indiscriminate extraction of its habitat. For this reason, the state agency Subsecretaría de Pesca y Acuicultura (SUBPESCA), Ministry of Economy, Development and Tourism, has established a closed extraction season in the period between December 1 and April 30 of the following year, both inclusive. In addition, it establishes a minimum extraction size of 30 mm of cephalothorax length, measured from the right orbit to the posterior end of the cephalothorax, according to Decree 145 [48].

It is worth it to mention that the quality of the water for the production of river shrimp is also important. Table 4 shows the main physical and chemical properties that a body of water must comply with.

**Table 4.** Physical and chemical water properties for shrimp farming [49].

Parameter	Optimal Range
Temperature	20–25 °C
Dissolved oxygen	7.00–10.00 mg L <sup>-1</sup>
pH	7.5–8.0
Ammonium	<0.50 mg L <sup>-1</sup>
Nitrates	4.00 mg L <sup>-1</sup>
Nitrites	0.25 mg L <sup>-1</sup>
Salinity	20 Practical Salinity Unit (PSU) during farming and reduction to 15 PSU in zoea 15 and to 12–10 PSU at the end of each cycle

### 2.5. Presence of Arsenic in Aquaculture Species

As mentioned above, the arsenic content of the water resource in the study area exceeds national and international regulations. This element can be accompanied by both fish and mollusks [50]. In the case of the former, they can house this element in the gills, the gastrointestinal tract, and skin [51], and it is distributed in the liver, kidney, skin, and scales (affinity of arsenites for keratin), gills, and muscle, where the inorganic arsenic is biotransformed into organic arsenic lipo- and water-soluble [52]. In relation to mollusks, such as river shrimp, arsenic is accompanied by shrimp cephalothorax (*Cryphiops caementarius*), this is evidenced in a study by Garcia, 2019. Where the levels of heavy metals of chromium, arsenic, lead, and mercury are indicated in shrimp from the Ocoña, Majes, and Tambo rivers, localities in Peru [53].

## 3. The Integrated Aquaculture Recirculation System

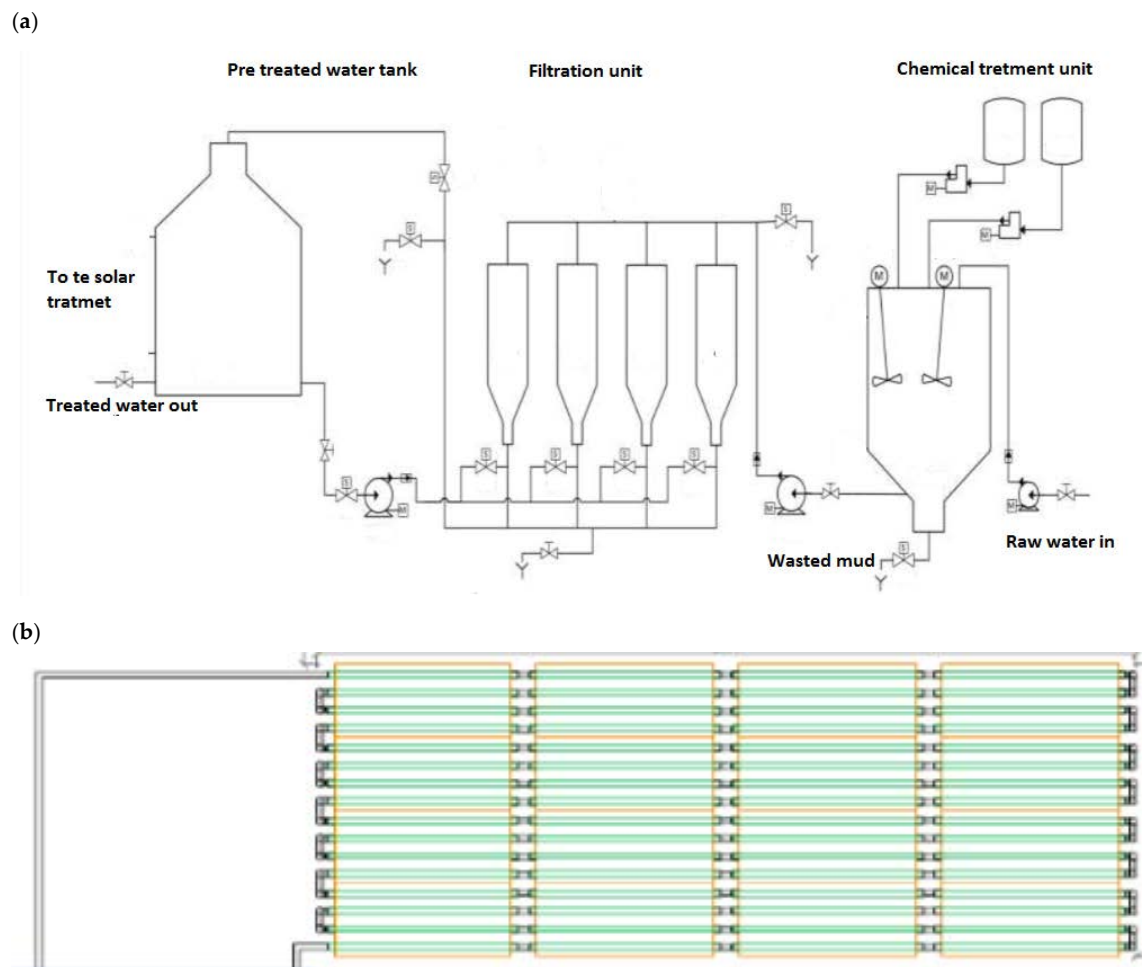
IARS was designed, built, and implemented in a period of 3 years, from January 2018 to September 2020, including the co-construction stage, which was of great relevance to incorporate aspects, such as the shrimp–fish relationship. Moreover, the land conditioning, planimetry, civil works, and the installation of three main components were carried out, as detailed below:

### 3.1. Component 1: Solar Water Treatment Plant

It is a process in which the quality of natural waters is improved, such as the waters of the Camarones River, through a physical–chemical processes and photochemical reaction using solar radiation. The Camarones is characterized by its natural waters (surface and underground) with high levels of arsenic, exceeding, by 100 times, the World Health Organization (WHO) normative [17], as a result of geothermal activity and volcanism in the Andes mountain range.

According to the above, the solar water treatment plant was designed and implemented considering the characteristics of the sector related to water quality, solar radiation, among others. This plant has a capacity of 9 m<sup>3</sup> day<sup>-1</sup> in an 8-h cycle, it consists of a system that includes a water pre-treatment system (filtration and coagulation stages) (Figure 4a) before entering the cylindrical parabolic concentrating solar collector, composed of 16 parallel modules (Figure 4b), in which 5 cm wide, 150 cm length interconnected glass pipes are used to ensure complete oxidation of the treated water, avoiding any harmful chemical to the fish. Through this plant and with the support of solar radiation, it is possible to reach arsenic concentrations within 0.03 and 0.05 mg L<sup>-1</sup>, removing 95% of the arsenic present in the natural waters of the Camarones River, complying with regulations. We should comment that, in a previous water filtering process, organic material (leaves, branches, among others), garbage, or some foreign body that could tap the system, was extracted.





**Figure 4.** (a) Schematic design of the filtration-coagulation water treatment plant. (b) Solar compound parabolic concentrator (CPC) reactors to be connected to the filtration unit (proper elaboration).

### Optimal Performance

The optimal feed flow rate ( $Q_a$ ) is  $10 \text{ m}^3$  and the product water ( $Q_p$ ) is  $9 \text{ m}^3 \text{ day}^{-1}$ , considering that the Camarones River water is brackish, it is assumed that the plant yield ( $Y$ ) is obtained from the Equation (1) [54]:

$$Y (\%) = Q_p / Q_a \times 100 \quad (1)$$

Replacing the plant yield ( $Y$ ), this corresponds to 90%. With the optimal flow rates of the feed water and the product plant water, the brine flow rate ( $Q_s$ ) is obtained. Replacing, in Equation (2), the load balance [54]:

$$Q_a = Q_p + Q_s \quad (2)$$

It results that  $Q_s$  is  $1 \text{ m}^3 \text{ day}^{-1}$ . This waste will be deposited in the desiccating pool for liquid waste, which will later be used to fertilize the land in the sector and as water for irrigation of ornamental plants in the integrated aquaculture recirculation system.

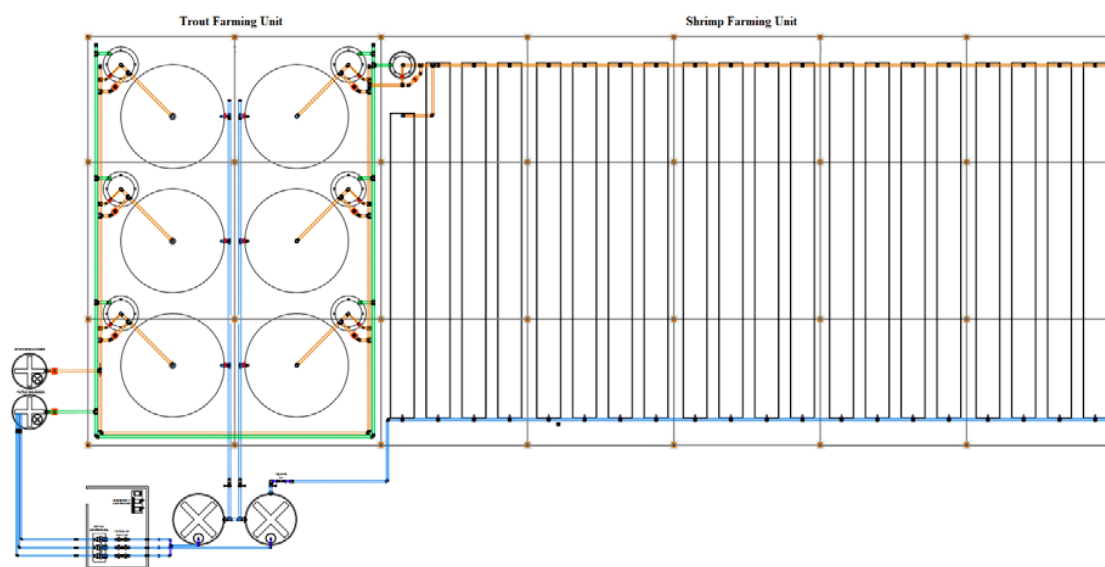
### 3.2. Component 2: Aquaculture Recirculation System

It is a terrestrial aquaculture recirculation system, where the water is partially reused and the simultaneous farming of shrimp and trout is achieved, providing a stable farming medium, which must be managed in an integral way [55].

The aquaculture recirculation system components are: (i) 6 tanks of galvanized corrugated steel for rainbow trout of 5.0 m in diameter and a nominal height of 1.76 m, with a maximum water

volume of 33 m<sup>3</sup>. The water reaches each tank through a central distribution pipe and lateral springs, which supply water to each farming unit. The flow is controlled by Polyvinyl chloride (PVC) valves, which, due to their arrangement, generate a circular movement of the water. (ii) Twenty tanks for river shrimp, which measure 17 m long by 1.2 m wide and have a column of useful water of 0.30 m, with a capacity of 6.12 m<sup>3</sup>, wooden tanks covered with plastic High Density Polyethylene (HDPE). The water supply is through a pipe installed at one end of the tank, with a valve to regulate the incoming water flow (Figure 5).

In addition, this system considered the installation of two accumulation tanks, of 2.0 m high, to take advantage of the water fall by gravity. This arsenic-free water from the solar water treatment plant will be used to simulate the river current, which will help with oxygenation of the farmed species, both fish and river shrimp.



**Figure 5.** Aquaculture recirculation system scheme (proper elaboration).

On the other hand, an air distribution pipe was arranged both for trout and shrimp, supplied by a blower, which will allow continuous aeration and oxygenation of the water column to ensure high levels of dissolved oxygen. Additionally, each tank (trout and shrimp) has two outlets; one connected to the recirculation system and the other to the general drain. The water that comes out of the tanks will pass through an underground PVC tube to the conical sedimentation tanks whose function is to retain the feces and the food that is not consumed. These clarifiers reduce solids and also allow solid waste to be removed into the desiccating pools for liquid industrial waste.

This system was designed for a maximum and ideal production of 8000 kg of products, considering 25% for river shrimp and 75% for rainbow trout.

It is worth mentioning that 6000 trout will be acquired for the start-up of this system, which will be transferred from the Río Blanco Farming Center located in the V region of Valparaiso to the integrated aquaculture recirculation system plant in the village of Camarones, crossing an approximate distance of 1869 km. With this transfer, the fish will have a mortality rate close up to 10%, with an average weight between 10.00 and 15.00 g [56].

For this species, a cultivation process is considered from the fattening phase, where the fish are farmed, reaching the commercial weight (0.50 to 1.00 kg).

The fattening units, such as raceways, circular tanks, or cages were used, where the recirculation system allows the reuse of water. In the future, fry are expected to appear, preferably raised in circular tanks to maintain a regular current and uniform distribution.

Regarding the availability of river shrimp for farming in the aquaculture recirculation system tanks, these will be extracted by shrimp farmers and members of the communal cooperative in the village of Camarones.

Among all of the advantages offered by this type of system, the principal is the reduced water consumption, and for this initiative, a system renewal was considered, between 5 and 10% of the entire farming volume per day [57]. On the other hand, these systems allow better opportunities in waste management, nutrient recycling, hygienic disease management, and greater control of biological contamination. In addition, with these systems, it is possible to opt for a greater variety of farming of hydro biological species, considering the production of fry until their fattening [58].

### 3.3. Component 3: Photovoltaic Plant

For an aquaculture recirculation system and solar water treatment plant operating, a photovoltaic plant was installed that supplies the electrical energy necessary for the operation and functioning of the different equipment in an integrated aquaculture recirculation system. In addition, a generator set was considered as backup in emergency situations.

The photovoltaic plant is located at 19°0'37.11" S, 69°51'25.88" W, with an elevation of 719 m, a slope of 7°, and an orientation of 336° northwest. Furthermore, it has a mean annual global solar irradiation onto an inclined plane of 2620 kWh m<sup>-2</sup>, and an annual temperature (at 2 m) of 18.8 °C. Meanwhile, for the daily consumption of 1355 kWh day<sup>-1</sup>, the following was considered:

- (a) In-grid plant, to generate, consume, and sell surplus electricity to the local electricity company, this project was covered by law 20.571 regarding the distributed generation or net billing of the Chilean Ministry of Energy. This law allows self-generation of energy based on non-conventional renewable energies and efficient cogeneration. In addition, this plant was registered by the Superintendence of Electricity and Fuels (SEF), and has the following components (Table 5):

**Table 5.** Energetic requirement for on-grid plant. Development company of the photovoltaic plant [59].

Item	Characteristics
80 polycrystalline silicon photovoltaic modules, brand Astronergy	Maximum power de 295 W
1 Three-phase inverter SMA Sunny Tripower	25,000 Wp
Power	25 kVA

- (b) Off-grid plant, it is a backup system that allows connecting the critical loads of integrated aquaculture recirculation system plant, which cannot be interrupted due to the fact that there are biological species that must receive aeration for the growth and development of the species (Table 6).

**Table 6.** Energetic requirement for Off-Grid plant. Development company of the photovoltaic plant [59].

Item	Characteristics
1 Studer hybrid inverter, single phase	800 W
Battery bank	24 Sonnenschein batteries (2 V cells) 1960 Ah

## 4. Circular Economy

The world is changing; economic, environmental, and social challenges that today's society faces are increasingly demanding, which makes it essential to change the extract–use–dispose economic model. In this sense, the principle of a “circular economy” is a good way to make the approach more sustainable. In the circular economy, system resources, energy, and materials are reused several times, considering minimal processing for each subsequent use, through a closed circuit [60]. As indicated

in [61], turning waste into a resource is an essential part of increasing our efficiency and moving towards a more circular economy.

Figure 6 shows the implemented system, which, through the three main components (solar water treatment plant, aquatic recirculation system and photovoltaic), considering the principles of the circular economy, can aspire to sustainability. The diagram of the integrated aquatic recirculation system plant begins with the generation and distribution of electrical energy obtained out of the Photovoltaic plant. Subsequently, the solar water treatment plant system produces  $9 \text{ m}^3 \text{ day}^{-1}$  of treated water and generates  $1 \text{ m}^3 \text{ day}^{-1}$  of liquid waste, which is sent to the desiccating pools for liquid waste. The treated water enters the trout and shrimp ponds in a first cycle, then the water begins to recirculate, passing through a filtration system. Once a day, the product is removed from the conical decanters and sent to the aerobic nitrifiers and then to the liquid waste drying pond.

It should be noted that the aquatic recirculation system allows a sustainable water management, which is a limited resource in the study area. In addition, the fact that this system is energetically sustained through renewable energies and solar radiation makes it considerable and replicable. Moreover, it aims to environment respectful food production of high economic performance, which is one of the current concerns of the food industry, and could be resolved with this [62].

In order to aspire to sustainable development through a circular economic model, it must be considered that operating the integrated aquatic recirculation system plant will generate a liquid waste of salts in aqueous solution and sludge through the solar water treatment and the aquatic recirculation system. This waste will be disposed in desiccating pools for liquid waste, where by decantation the supernatant liquid will be used to irrigate the green areas in integrated aquatic recirculation system plant, halophyte species resistant to saline waste [63]. On the another hand, the sludge resulting from aquaculture systems produced by feces and food remains have higher carbon (C), nitrogen (N), and phosphorus (P) contents than natural sediments [64], nutrients that will be used as plant fertilizer [65]. The plant species to be farmed are typical from the area, such as carrot, onion, garlic, alfalfa, among others.

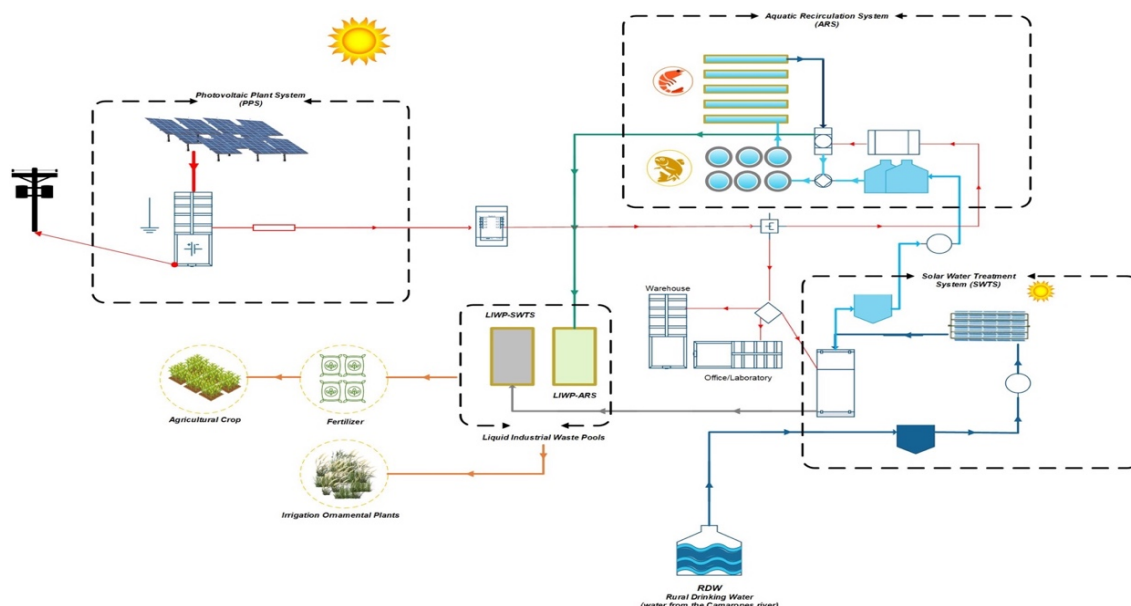


Figure 6. Integrated aquatic recirculation system plant system (proper elaboration).

As for arsenic naturally present in surface water, it does not present serious problems when it remains in water aqueous solution, since the endemic plants, according to research studies [66], have shown that this element accumulates in the roots, therefore, the probability of being transferred to the animal or human trophic chain is much lower. On the other hand, shrimp or fish can accumulate arsenic in their body and be transferred to humans [10,56]. This is because fish and mollusks are

considered bio indicators, which allow evaluating the presence of toxic substances and present characteristics of concentrating and metabolizing pollutants [67].

The simultaneous production of agricultural and aquaculture products is not a novelty. There are several initiatives and studies in this regard. However, achieving this diversification of products from solar-treated water is very relevant. In this sense, this study considers a circular economy approach [60,61], to manage the waste generated by the integrated aquatic recirculation system, whose waste can be valorized through agricultural products and savings in water consumption. In addition, through the installation and implementation of the integrated aquatic recirculation system, it contributes, reducing overexploitation of the aquaculture on land and promoting a more sustainable use of aquatic resources, since it generates a sustainable management of the river shrimp resource, by restoring the species taken from the river.

## 5. Discussion and Conclusions

This work combines three main components, aquatic recirculation system, solar water treatment, and photovoltaic plan system, which shape an integrated system that supports the sustainability of Camarones. To achieve this, different aspects were evaluated, from (i) the co-construction methodology, integrating the social and environmental part, (ii) promoting the river shrimp farming in the aquatic recirculation system, a species obtained from the river that crosses the Camarones Valley farmed in arsenic-free water, (iii) this water obtained through the treatment system allows a regulated and limited water consumption, and finally (iv) use of solar energy for the production of electrical energy.

In addition, this initiative encourages the mitigation of environmental impacts, considering: the reduction of greenhouse gases, the reuse of liquid waste, and sludge for irrigation and as fertilizers, respectively. Moreover, value is added by producing agriculture fertilizers from the integrated aquaculture recirculation system waste, complementing with the sale of aquaculture species, such as shrimp and trout.

Moreover, it is possible to consider the adoption of the principles of the circular economy in the integrated aquaculture recirculation system plant. Furthermore, the simultaneous obtaining of halophytic plants and ornamental forage species that would support the preservation of the natural ecosystem of the sector is allowed. In addition, to obtain nutrients through the aquaculture recirculation system, a source of nitrogen and phosphorus, for agricultural crops, represents an alternative for the final disposal of these residues.

The important thing, when reusing, is to promote a zero liquid discharge, and by adding value to the waste, this initiative becomes sustainable and friendly to the environment, fitting all of the principles and strategies of the circular economy. For this reason, it is necessary to change the way in which society produces and consumes.

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