Sustainable recirculating aquaculture model (RAM) and its part in circular economy aquatic food generation

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Abstract

This study involved the cultivation of river shrimp with extensive ultraviolet radiation for the long-term growth of Camarones, a hamlet in Chile. An aquaculture cultivation facility was established utilizing water recirculation to yield 8500 kilograms of river shrimp and rainbow trout annually, in a 30:70 ratio, respectively. This was created by considering (1) the idea of assisting resilient communities through the concepts of the circular economics, (2) the utilization of solar water intervention methods for the growing of these plants to diminish arsenic levels in the untreated waters of the Camarones River, and (3) strategies for enhancing the value of the byproducts from the manufacturing plant to improve agriculture and ensure water preservation for the environment. This endeavor will utilize solar energy and irradiation to generate electricity and employ the process of photosynthesis to eliminate arsenic from the water. This initiative adheres to 10 of the 12 guiding principles of the Circular Economy, positioning it as a viable solution for regions with analogous features worldwide.

Keywords: Aquaculture, Circular economy, Aquatic food generation, Sustainability

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Introduction

Water is vital for energy generation, agricultural production, socioeconomic advancement, and ecological systems (Qin *et al.*, 2022). Water scarcity impacts 42% of the world population, while 82% of wastewater reenters the environment untreated or unrecycled. One hundred forty-five million individuals lacked access to adequate nutrition. Due to the Coronavirus Disease 2019 (COVID-19), around 275 million individuals are projected to confront famine by the end of 2020 (Chatterjee and Sanyal, 2024). In this regard, a significant problem exists in supplying food and other necessities to a global population projected to surpass nine billion people by 2050. Complete access to sufficient food will be essential in developing nations. Since 2000, a significant escalation in food costs has been seen, attributed to climate change, rising energy prices, and speculation in the stock market (Ray, Banerjee and Das, 2021).

Due to alterations in land use, dispersion of habitat, overexploitation, illicit trade in wildlife, pollution, and global warming, people are approaching a significant extinction of species, jeopardizing the natural beauty of the land and its capacity to fulfill human requirements (Gray *et al.*, 2021; Narayanan and Rajan, 2024). United Nations (UN) research indicates that catch fisheries from the globe's oceans have likely attained their maximum capacity, impacting around 600 million individuals globally (Campanati *et al.*, 2022; Menon and Deshpande, 2023).

Fish is a vital food supply for 4 billion individuals worldwide, providing at least 60% of the plant-based proteins and key minerals consumed by 450 million individuals in the most impoverished nations (Patankar and Kapoor, 2024; Das *et al.*, 2023). In this setting, the Food and Agriculture Organization (FAO) reported that 2019 worldwide production from aquaculture of edible fish reached 85 million tons, with sales amounting to USD 245.2 billion, yielding 12.4 kg of fish per capita in 2017. Fish from freshwater pond agriculture significantly contributes to aquaculture manufacturing, achieving 48.2 million tons of fish in 2018 (Topić Popović *et al.*, 2023; Rahman and Begum, 2024).

Recognizing that equitable growth is unattainable without resilient livelihoods, the research selected Camarones, a town in the Arica and Parinacota Area in northern Chile, as an exemplar of resilience. This town has an inland desert environment, over 1200 meters above sea level, devoid of coastal oceanic influences (Wang *et al.*, 2019). The Camarones River is defined by aridity, exhibiting negligible annual precipitation and typical temperatures of 19°C. The days predominantly feature clear skies and lower humidity than the coastline desert environment, with a median relative moisture of 60% (Menon and Deshpande, 2023).

A pilot-scale solar power facility for cultivating river shrimp has been set up in this town by the Chilean Sunlight Studies Institute, utilizing solar water treatment methods to diminish the arsenic levels in the water supply of the Camarones rivers (Chandravanshi and Neetish, 2023).

Principal Recycling Prospects in Aquaculture

Implementing conventional and innovative recycling techniques in aquaculture holds significant promise for enhancing sustainability and substantially boosting production levels (Cafaro, 2022). Reclaimed solids, dissolved nutrients, and seafood by-products can be repurposed to improve farming and other sectors, including agriculture and nutritional supplements. For instance, the recycling of the omega-3 fatty acids from marine by-products, along with the utilization of bioremediating microorganisms and filter-feeders (such as polychaetes and aquatic organisms), might substantially augment the availability of omega-3 oils, yielding considerable economic and health advantages (Nazarova and Bobomuratov, 2023).

Energy produced from sludge elimination, purified water obtained from biological remediation, and repurposed nutrients via linked aquaculture facilities could contribute to the sustainability of intensive arable agriculture (Aliyari, 2024). The subsequent recycling approaches are crucial in developing a sustainable circular economy within aquaculture.

Recovery of By-products

Fishing by-products can be reclaimed for application in several high-value sectors, including fishing, farming, and the pharmaceutical and food sectors. The predominant repurposing of marine by-products involves their reintegration into food or feed components for agriculture. Seafood by-products, comprising high-quality proteins (30-60%) and calories (12% lipids), are extensively utilized in animal and pet food. An opportunity exists to optimize the utilization of sewage generated from the transformation of trimmings and fodder into fish meal and fish oils. Wastewater generated from processing seafood leftovers (e.g., 1400 m^3 per day from 150 tons of tuna per day) can be repurposed as a substrate for algae cultivation following solid filtering. From 1 m^3 of the processing of fish effluent (comprising 85% organic matter, 5.2% total nitrogen, and 0.5% total phosphorus), it is possible to yield over 370 g of microbial biomass each day, including 60 g of lipids per day (Abbas *et al.*, 2024).

Discarded shells from bivalve farming can ameliorate soil acidity, provide animals with minerals, manufacture building supplies, serve as natural materials, and act as alkalinity buffers for natural reefs and rehabilitation initiatives (Fatima *et al.*, 2024). Oyster shells have been regarded as filtration substrates for removing phosphorus (PO) from wastewater, while shell extracts are utilized to enhance microalgae for biodiesel synthesis.

Recycling of Wastewater Materials

Land application is the predominant recycling method for hatchery settling lakes, basins, and RAS wastewater solids. Nutrient-dense aquaculture sludges serve as significant bioresources for terrestrial plant fertilization, enhancing or preserving soil structure, while mitigating ecological repercussions associated with mining and synthetic fertilizers. Aquaculture sludge typically has fewer hazardous and health-related constituents than sludges from industrial and residential treatments. The decomposition of aquaculture wastewater (e.g., at 45°C for many days), in conjunction with dehydrating sludge and adjustment of the C/N ratio as necessary, can diminish biosolid infections. Sediments collected from ponds following each aquaculture manufacturing process are desiccated and repurposed for fertilizing lakes, mangrove replanting, soil enrichment, and fodder grass.

Nutrient Recovery from Sewage

Aquaculture wastewaters are nutrient-rich, including high levels of nitrogen, phosphorus, and trace minerals such as potassium, calcium, magnesium, iron, copper, and manganese, which can produce bacterial and algal biomass for valuable reuse. Numerous studies have shown that liquid side streams are valuable recyclable nutrient supplies for economically producing self-sustaining, heterotrophic, and mixotrophic algae, microalgae, and seaweeds.

Upcycling Nutrient Networks

Bioflocculation Technique (BFT) (Menon and Patil, 2023) is an innovative, economically viable, eco-friendly bioremediation solution for terrestrial aquaculture operations. When wastewater exhibits a C/N ratio over 12, BFT can diminish ammonium content around 20% more rapidly than nitrification and 32% more cost-effectively than traditional biofilters. BFT possesses significant potential as a cost-effective solution for enhancing nutrients and output within the nutritional web associated with multi-trophic farming. Biofloc, rich in vital fatty acids, organic amino acids, carotenoids, and chlorophyll, nutrients, and trace elements, possesses significant nutritional significance for the production of zooplankton, squid, red Nile tilapia, and oysters, potentially lowering feed expenses. In intensive shrimp aquaculture cultures, the utilization of biofloc has resulted in a net productivity increase of 7-42% compared to traditional methods. It has been shown that inoculating bioflocs with specific microbes can be a probiotic to mitigate pathogen burdens in prawns and fish, especially during their early life phases.

Proposed Recirculating Aquaculture Model (RAM)

The RAM was developed, constructed, and deployed over three years, encompassing a co-construction phase for integrating elements such as the shrimp-fish interaction. The land training, planimetry, civil engineering works, and the installation of three principal components were executed, as outlined below:

Part 1: Solar Water Purification Facility

The approach enhances the purity of pure waters, such as those of the Camarones River, by physical-chemical methods and photochemical reactions utilizing solar energy. Camarones is distinguished by its natural waters, both surface and subterranean, which contain arsenic levels surpassing the World Health Organization (WHO) standard by 100 times, attributable to geothermal energy and volcanic activity in the Andes Mountains.

The solar water purification facility was built and implemented considering sector-specific factors, including water quality and sun radiation. This facility has a capacity of 8 m^3 per day within an 8-hour cycle. It is comprised of a system that involves a water prior treatment process (filtering and blood coagulation stages) before going into the parabolic, emphasizing solar cylinder collector, consisting of 15 parallel components. Interrelated glass pipes, measuring 6 cm in width and 160 cm in length, are utilized to ensure the complete oxidation of the cleaned water, thereby preventing any harmful chemicals from affecting the fish. Using solar radiation, this facility can achieve levels of arsenic between 0.02 and 0.06 mg/L, effectively eliminating 92% of the arsenic found in the freshwater of the Camarones River, thereby adhering to regulatory standards. Notably, organic matter (such as leaves and branches), debris, or any extraneous objects that could obstruct the system were removed during a prior water filtration process.

Part 2: Aquaculture Recirculating System

This terrestrial farmed recirculating system partially reuses water and facilitates the concurrent cultivation of shrimp and trout, necessitating comprehensive management of the farming environment. The farmed recirculation network includes six galvanized corrugated stainless-steel tanks for rainbow trout, each having a diameter of 6.0 meters and a nominal height of 1.82 meters, accommodating an aggregate water capacity of 35 cubic meters. Water is delivered to each tank by a central distributing line and lateral origins, which provide water to each agricultural unit. The flow is regulated by Polyvinyl chloride (PVC) devices, which, owing to their configuration, provide a circular motion of the water. Twenty containers for river shrimp, each measuring 16 m in length and 1.3 m in width, with a usable water height of 0.35 m, and an overall volume of 6.4 m³, constructed from wood and coated with High-Density Polyethylene (HDPE). The water supply is facilitated by a pipe at one end of the tank, equipped with a valve to control the water inflow.

This arrangement incorporated two accumulation containers, each 2.5 meters high, to utilize gravitational water flow. The arsenic-free water generated by the solar purification facility will replicate the river current, facilitating oxygenation of the cultivated species, including fish and river prawns.

Conversely, an air distribution line was installed for trout and shrimp, powered by a blower, facilitating continual aeration and oxygenation of the water columns to maintain elevated oxygen levels. Each tank (trout and shrimp) has two shops: one linked to the recirculation system and another to the main drainage channel. The water from the tanks will traverse a submerged PVC conduit to the conical sedimentation containers designed to contain excrement and uneaten food. These clarifications diminish solids and facilitate substance removal into the dehydrating pools designated for liquid recyclables.

The setup was engineered for an optimal production capacity of 8100 kg of goods, allocating 30% to river shrimp and 70% to the rainbow trout. It is noteworthy that 6500 fish will be procured to initiate this process, which will be transported from the Río Blanco Farming Position in the V region of Valparaiso to the incorporated fish farming recirculation structure facility in the village of Camarones, covering a distance of roughly 1900 km. This transfer will result in a mortality rate of approximately 12%, with an average weight ranging from 12.5 to 14.5 g. This species undergoes a culture procedure beginning at the fattening stage, during which the fish are raised to a marketable weight of 0.5 to 1 kg. The feeding systems, including raceways, round tanks, or cages, utilize a system for recirculation that facilitates water reuse. In future generations, fry are anticipated to be cultivated, ideally in circular tanks to ensure consistent current and even dispersion.

Part 3: Photovoltaic Facility

A photovoltaic system was erected to provide the electrical energy required to run various equipment within an integrated marine recirculation network and solar water treatment facility. A generator set was deemed necessary as a contingency for emergencies. Additionally, it possesses a mean annual global solar irradiance on an angled plane of 2600 kWh m-2, and a yearly temperature (at 2 m) of 17.2 °C. In the meantime, the following was considered for the daily usage of 1400 kWh.

(a) An in-grid plant designed to create, use, and sell excess power to the local utility business, this endeavor is governed by distributed output or net billing as established by the Chilean Ministry of Electricity. This legislation permits energy generation via non-conventional renewable sources with effective cogeneration methods. This facility had been recorded with the Superintendence of Energy and Fuels (SEF).

(b) The off-grid plant serves as a backup system that facilitates the connection of essential loads within the incorporated aquaculture recirculation structure, which cannot be disrupted due to the necessity of oxygenation for developing and spreading biological organisms.

Circular Economy

The world is evolving; contemporary society’s economic, environmental, and social difficulties are becoming more exigent, necessitating a transformation of the extract-use-dispose economic paradigm. In this regard, the notion of a "circular economy" effectively enhances the method's sustainability. In a circular economy, assets, energy, and materials are repeatedly reused within a closed-loop system with minimal processing for each successive application. Transforming waste into a resource is crucial for enhancing efficiencies and advancing a more sustainable economy.

The established system, comprising three main elements (solar water purification facility, aquatic recirculating system, and solar technology), adheres to the fundamentals of the circular economy and aims for sustainability. The schematic of the combined aquatic recirculating system commences with generating and transmitting electrical power derived from the photovoltaic plant. The solar wastewater treatment plant system yields 8 m³ per day of filtered water and generates 2 m³ per day of solid waste, which is directed to the evaporation pools for disposal. The purified water initially flows into the trout and shrimp ponds, after which it recirculates through a filtering system. Daily, the product is extracted from the conical decants and transferred to the aerobic nitrifiers before proceeding to the liquid waste drying pond.

The aquatic recirculating system facilitates responsible water use, a scarce resource in the research area. The system's reliance on renewable energy sources and solar radiation renders it viable and reproducible. It seeks to achieve environmentally respectful food manufacturing with high economic efficiency, addressing a significant worry within the food business that might be mitigated through this approach.

To achieve equitable growth via a circular economic approach, it is essential to recognize that the operation of the incorporated aquatic recirculating structure will produce liquid waste consisting of saline fluids and sewage due to solar water purification and the recirculating process.

The material will be dealt with in dehydrating pools for wastewater, where its liquid form will be decanted for use in irrigating green regions within a unified aquatic recirculating system, utilizing halophyte organisms that are immune to saline wastes (Figure 1). The sludge generated from aquaculture facilities, which is composed of feces and food remnants, contains elevated levels of carbon ©, nitrogen (N), and phosphorus (P) compared to natural debris, elements that can be utilized as fertilizer for plants. The cultivated plant species are indigenous to the region, including carrot, onions, garlic, and alfalfa.

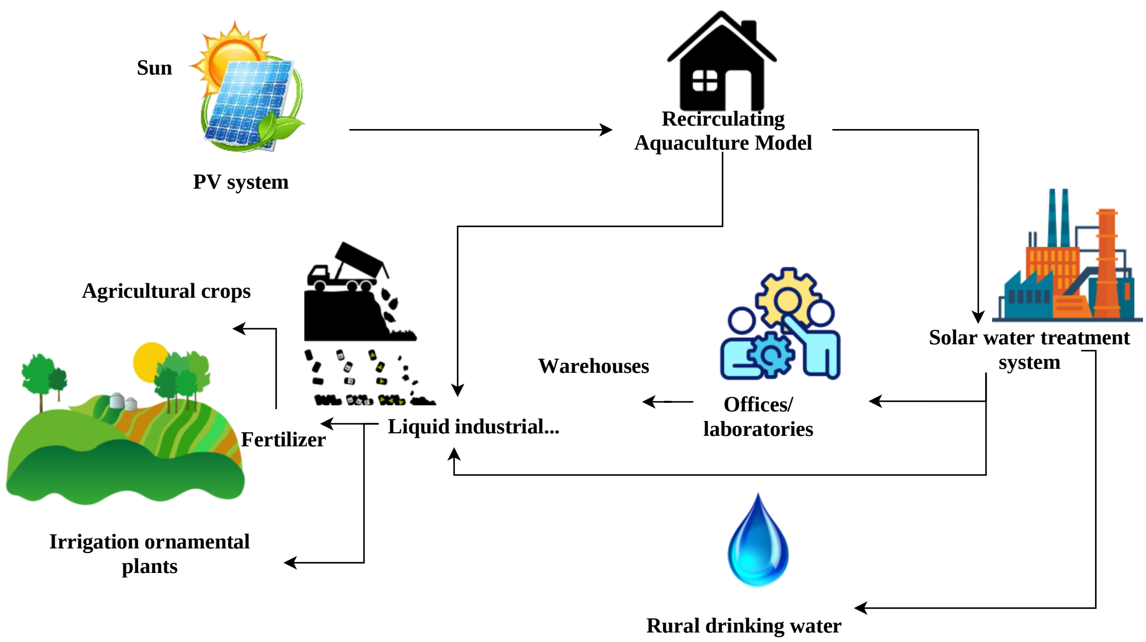

Figure 1: Structure of the RAM.

Arsenic, which is found in surface water, does not pose significant issues. At the same time, it remains in aqueous solutions, as endemic plants, according to research, have demonstrated that this element builds up in their roots, thereby reducing the likelihood of its move to the human or animal trophic chain. Shrimp and fish can bioaccumulate arsenic, which is transmitted to humans. Fish and mollusks serve as bioindicators, enabling the assessment of harmful compounds and exhibiting traits of concentrating and metabolizing contaminants.

The concurrent cultivation of agricultural and aquatic goods is not a novelty. Numerous projects and studies exist in this context. Attaining this variety of goods derived from solar-treated waters is highly significant. The investigation adopts a circular economy strategy to handle the waste produced by the integrated aquatic recirculation structure, which can be celebrated through crops and reductions in water usage.

The setting up and operation of the incorporated aquatic recirculating structure mitigates the excessive use of terrestrial aquaculture. It fosters a more environmentally friendly utilization of water resources by facilitating the long-term preservation of the river's shrimp population, thereby replenishing the species extracted from the river.

Conclusion

This project integrates three main parts: an aquatic recirculating structure, solar water purification, and a photovoltaic system, collectively fostering the future viability of Camarones. To accomplish this, various elements were assessed, including (i) the co-construction technique, which integrates ecological and social components, (ii) the promotion of river shrimp farming within an aquatic recirculating structure, utilizing a species sourced from the river traversing the Camarones Valley, cultivated in arsenic-free water, (iii) the water acquired through the purification structure facilitates controlled and limited intake, and lastly (iv) the utilization of sunlight for electrical power generation.

This effort promotes mitigating adverse ecological consequences by emphasizing decreasing greenhouse gas emissions, reusing liquid waste, and applying sludge for agriculture and nutrients. Value is enhanced by generating agricultural fertilizers from the byproducts of the complete farmed recirculating structure, supplemented by the sale of fish from aquaculture, including shrimp and trout.

Implementing principles from the circular economy in the combined aquaculture recirculating system plant is feasible. The concurrent acquisition of halophytic vegetation and decorative species of forage that would facilitate the conservation of the sector's natural environment is permitted. Acquiring nutrients via a marine recirculating system is a substitute for the final disposal of these leftovers, supplying phosphorus and nitrogen for crop cultivation.

The crucial aspect of reuse is to advocate for zero liquid emission; by enhancing the value of trash, this project becomes ecologically sound and environmentally benign, aligning with the concepts and tactics of a circular economy. It is imperative to alter the methods by which society creates and consumes.

References

Abbas, L.M., Shivraj, K.S., Selvi, U.P., Balasubramani, R. and Dhanasekaran, S., 2024. Exploring the Relationship Between Academic Science and Economics Through Biofuel Research: A Scientometric Analysis. *Indian Journal of Information Sources and Services, 14*(1), pp.85-92. https://doi.org/10.51983/ijiss-2024.14.1.4112

Aliyari, M., 2024. Architectural Designing the Nursing Homes in Tehran City (As A Sample). *Archives for Technical Sciences*, *1*(30), pp.1-14. https://doi.org/10.59456/afts.2024.1630.001M

Cafaro, P., 2022. Reducing human numbers and the size of our economies is necessary to avoid a mass extinction and share Earth justly with other species. *Philosophia*, *50*(5), pp.2263-2282. https://doi.org/10.1007/s11406-022-00497-w

Campanati, C., Willer, D., Schubert, J. and Aldridge, D.C., 2022. Sustainable intensification of aquaculture through nutrient recycling and circular economies: more fish, less waste, blue growth. *Reviews in Fisheries Science & Aquaculture*, *30*(2), pp.143-169. https://doi.org/10.1080/23308249.2021.1897520

Chandravanshi, N. and Neetish, K., 2023. Diurnal Variations in Greenhouse Gas Emissions from a Macrophyte-Covered River. *Aquatic Ecosystems and Environmental Frontiers*, *1*(1), pp.11-15.

Chatterjee, A., and Sanyal, S., 2024. From production to market: Uncovering the complexities of COVID-19's impact on fisheries and aquaculture. *International Journal of Aquatic Research and Environmental Studies*, *4*(2), pp.37-52. http://doi.org/10.70102/IJARES/V4I2/3

Das, S.K., Mondal, B., Sarkar, U.K., Das, B.K. and Borah, S., 2023. Understanding and approaches towards circular bio-economy of wastewater reuse in fisheries and aquaculture in India: an overview. *Reviews in Aquaculture*, *15*(3), pp.1100-1114. https://doi.org/10.1111/raq.12758

Fatima, A., Singh, P., Pandey, V.K., Singh, R. and Rustagi, S., 2024. Exploring the significance of protein concentrate: A review on sources, extraction methods, and applications. *Food Chemistry Advances*, p.100771. https://doi.org/10.1016/j.focha.2024.100771

Gray, K.J., Bordt, E.A., Atyeo, C., Deriso, E., Akinwunmi, B., Young, N., Baez, A.M., Shook, L.L., Cvrk, D., James, K. and De Guzman, R., 2021. Coronavirus disease 2019 vaccine response in pregnant and lactating women: a cohort study. *American journal of obstetrics and gynecology*, *225*(3), pp.303-e1. https://doi.org/10.1016/j.ajog.2021.03.023

Menon, K. and Patil, S., 2023. Assessing Terminology Gaps in Global Health Guidelines: AWHO Terminology Audit. *Global Journal of Medical Terminology Research and Informatics*, *1*(1), pp.5-8.

Menon, S. and Deshpande, K., 2023. Climate-induced Migration and Its Impact on Rural Demographic Patterns. *Progression journal of Human Demography and Anthropology*, *1*(1), pp.5-8.

Narayanan, L., and Rajan, A., 2024. Artificial Intelligence for Sustainable Agriculture: Balancing Efficiency and Equity. *International Journal of SDG's Prospects and Breakthroughs*, *2*(1), pp.4-6.

Nazarova, J. and Bobomuratov, T., 2023. Evaluating the Clinical Utility of Genetic Testing in Guiding

Medication Selection. *Clinical Journal for Medicine, Health and Pharmacy*, *1*(1), pp.64-72.

Patankar, V. and Kapoor, M., 2024. Process Optimization of Filtration in Crystallization-Based Product Recovery. *Engineering Perspectives in Filtration and Separation*, *2*(1), pp.5-8.

Qin, J., Duan, W., Chen, Y., Dukhovny, V.A., Sorokin, D., Li, Y. and Wang, X., 2022. Comprehensive evaluation and sustainable development of water–energy–food–ecology systems in Central Asia. *Renewable and Sustainable Energy Reviews*, *157*, p.112061. https://doi.org/10.1016/j.rser.2021.112061

Rahman, S. and Begum, A., 2024. Applied Mechanics for Mechanical Engineers: Principles and Applications. *Association Journal of Interdisciplinary Technics in Engineering Mechanics*, *2*(1), pp.13-18.

Ray, A., Banerjee, S. and Das, D., 2021. Microalgal bio-flocculation: present scenario and prospects for commercialization. *Environmental Science and Pollution Research*, *28*, pp.26294-26312. https://doi.org/10.1007/s11356-021-13437-0

Topić Popović, N., Lorencin, V., Strunjak-Perović, I. and Čož-Rakovac, R., 2023. Shell waste management and utilization: Mitigating organic pollution and enhancing sustainability. *Applied Sciences*, *13*(1), p.623. https://doi.org/10.3390/app13010623

Wang, Y., Xiao, M., Miao, Y., Liu, W., and Huang, Q., 2019. Signature Scheme from Trapdoor Functions. *Journal of Internet Services and Information Security*, *9*(2), pp.31-41.