

CIRCULAR BIOECONOMY APPLICATIONS FOR SUSTAINABLE BIOMASS MANAGEMENT SUPPORTING THE GREEN TRANSITION IN INSULAR REGIONS

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Abstract

Insular regions face challenges such as energy deficit, a declining agricultural sector, deteriorating water and soil quality, a rise in the risk of natural disasters brought on by climate change, coastal pollution, ineffective biowaste management, deteriorating ecosystems, a loss of biodiversity, etc. Circular and resource-efficient economic models, which consider the entire material cycle to promote reuse as well as waste reduction and efficient resource utilization, are increasingly replacing linear economic models based on production-consumption-disposal systems. A bioeconomy covers a wide range of sectors and systems which are based on biological resources (animals, plants, microorganisms, and biomass, including organic waste), their functions and principles. The transition to circular bioeconomy will be further reinforced through the development and uptake of innovative technologies as well as the training of scientists and researchers through the collaborative ecosystem at national and international level.

This paper presents the research infrastructure and two selected representative case studies developed within the framework of the Center for Sustainable and Circular Bioeconomy of the University of the Aegean (Aegean_BIOECONOMY).

*The first case study investigates the cultivation of *Arthrospira* (*Spirulina*) *platensis* on diluted, non-sterile cheese whey, evaluating the effects of substrate concentration, pH and illumination on biomass production and nutrient consumption. The results show that alkaline conditions and light/dark photoperiods significantly enhance biomass productivity, while achieving high removal efficiencies for organic matter and nutrients, highlighting the feasibility of simultaneous wastewater treatment and biomass production. The second case study examines the production of bioplastics (polyhydroxyalkanoates - PHAs) using mixed microbial cultures under long-cycle feast-famine operation. Effective enrichment of PHA-storing microorganisms and substantial intracellular polymer accumulation were achieved, despite operational challenges related to sludge viscosity and aeration.*

Overall, the findings demonstrate that biological valorization pathways can convert locally agro-industrial streams into value-added bioproducts, supporting resource efficiency, waste reduction and regional resilience. The study underscores the role of dedicated research infrastructures in enabling circular bioeconomy solutions tailored to insular environments and provides a transferable framework for sustainable regional development aligned with European bioeconomy and climate objectives.

Key words: Circular bioeconomy, island sustainability, research infrastructure, green transition, agro-industrial waste, bioplastics, cyanobacteria

Introduction

The transition to a circular bioeconomy is essential for achieving sustainability, environmental protection, and economic modernization in regions that are highly dependent on natural resources and ecosystem services. Bioeconomy encompasses all sectors that rely on biological resources (biomass, organic waste, organisms) and integrates land, marine ecosystems, primary production sectors (agriculture, forestry, fisheries, aquaculture) and industrial applications for food, materials, and energy production. Embedding circularity and sustainability within this framework aligns renewable biological resource utilization with environmental, economic, and societal objectives (EC, 2020; UN, 2020).

In a linear economy, as it is in most European insular regions the current situation, materials are taken from the Earth to be used in product making and are eventually thrown away as waste. In the case of circular economy, by contrast, waste is not being produced in the first place. The circular economy is a system where materials never become waste and nature is regenerated. Products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. A circular system can help in tackling climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources. The three basic principles driven by design are eliminating waste and pollution, circulating products and materials at their highest value, and regenerating nature and are visually represented by the butterfly diagram (<https://www.ellenmacarthurfoundation.org/>), (Figure 1).

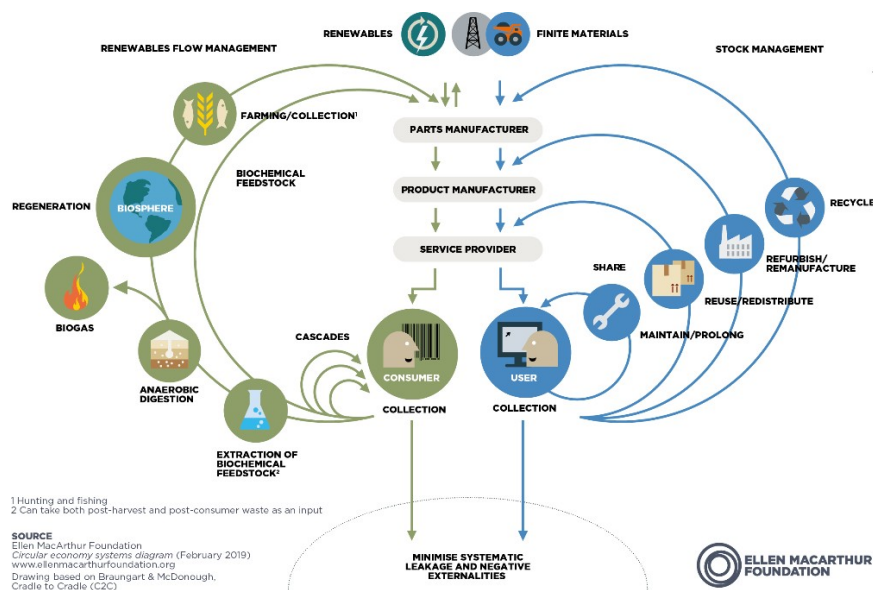


Figure 1. Visualising circular economy (the butterfly diagram)

The current research is focused on the biological cycle — recovering, treating, and valorizing bio-resources in ways that reduce pressure on ecosystems and promote sustainability. In islands, where resource limitations and waste management challenges are significant, circularity is not only environmentally beneficial but also economically strategic. Insular regions face distinctive challenges — limited land area, resource scarcity, seasonal tourism pressures, and logistical constraints — which require tailored solutions for sustainable development. In Greece, the Aegean islands represent a cluster of such regions where circular bioeconomy concepts can drive the green transition by enhancing resource efficiency, supporting ecosystem services, and creating sustainable employment opportunities. All these, make them ideal testbeds for circular solutions.

Research and innovation initiatives have increasingly focused on circular bioeconomy solutions tailored to local environmental and socio-economic conditions. This paper provides a general description of the integrated research activities and innovative applications developed by the Center for Sustainable and Circular Bioeconomy of the University of the Aegean, highlighting their contribution to the green transition of insular areas.

Selected case studies and research results are presented related to the sustainable production and management of biomass, which is considered particularly important for the islands of the North Aegean Region where the primary/agri-food sector is the key pillar of economic development. Olive oil, cheese, wine, milk, as well as other products complete the basket of famous products of the region, due to the combination of the special geoclimatic conditions of the Northern Aegean region and the traditional production practices – similar to other regions in the Mediterranean. During production and processing, significant amounts of by-products and residues - biowaste - are produced. The management of waste from olive mills, cheese factories and wineries, slaughterhouse residues, livestock waste and residues from fruit processing is a major environmental as well as economic problem for businesses. The seasonal variation and the special characteristics of these by-products make it even more difficult to find sustainable and efficient management solutions.

The agri-food sector is a major contributor to organic waste generation, with the dairy industry producing large volumes by products such as cheese whey, which is characterized by high concentrations of biodegradable organic matter, as well as significant levels of nitrogen and phosphorus (Yadav et al., 2015; Zandona et al., 2021). When improperly managed, cheese whey disposal can lead to severe environmental pollution, particularly in aquatic ecosystems, due to oxygen depletion and eutrophication (Lucakova, 2022). Despite the development of several valorization pathways, including protein recovery and fermentation processes, sustainable and economically viable whey management remains a challenge, especially for small- and medium-scale dairies and geographically constrained regions such as islands (Kalantzis et al., 2023; Nazos et al., 2023).

Microalgae and cyanobacteria cultivation has emerged as a promising strategy for the integrated treatment and valorization of nutrient-rich wastewaters. These microorganisms can assimilate inorganic and organic nutrients while producing biomass rich in proteins, pigments, lipids and bioactive compounds (Koller et al., 2014; Calicioglu & Demirer, 2022). Among them, *Arthrospira* (*Spirulina*) *platensis* is of particular interest due to its high growth rates, tolerance to alkaline conditions and ability to outcompete contaminating microorganisms under elevated pH and salinity (Sukenik et al., 2009; Delrue et al., 2017). These characteristics make *A. platensis* especially suitable for cultivation on non-sterile waste-derived substrates, thereby reducing operational complexity and production costs.

Agro-industrial waste and residues can also be valorized to meet the sustainable consumption goals, through their conversion to bioplastics. The extensive use of conventional,

fossil-based plastics has generated severe environmental challenges, including persistent pollution, microplastic accumulation and increasing greenhouse gas emissions associated with their production and disposal. A significant share of global plastic production is linked to short-lived applications, particularly packaging, which rapidly become waste and intensify environmental pressures (Ellen MacArthur Foundation, 2022). In response, biodegradable and bio-based alternatives have gained increasing attention as part of circular bioeconomy strategies aimed at decoupling material production from fossil resources. Among bioplastics, polyhydroxyalkanoates (PHAs) are considered especially promising due to their complete biodegradability in natural environments, favorable thermoplastic properties and wide range of applications (Koller et al., 2014). PHAs are intracellular polyesters synthesized by microorganisms as storage compounds, typically under conditions of excess carbon and limitation of essential nutrients such as nitrogen or phosphorus.

In this paper, information and results on the application of innovative solutions for the valorisation of agro-industrial waste and residues are presented as case studies and specifically:

- The evaluation of *Arthrospira* (Spirulina) *platensis* growth on cheese whey
- The investigation of the production Polyhydroxyalkanoate (PHA) bioplastics of consistent composition from organic waste

Research Infrastructure and methodological framework

Mission and Objectives

The Center for Sustainable Circular Bioeconomy and Energy (Aegean_BIOECONOMY) is a multi-disciplinary research infrastructure hosted by the University of the Aegean (Department of Environment) aimed at supporting the transition from a linear to a circular bioeconomy in the insular regions of the North and South Aegean (Greece). It was established within the framework of the action “Reinforcement of the Research and Innovation Infrastructure”, co-financed by Greece and the European Union through the European Regional Development Fund. The project had a total budget of approximately €1.37 million and a duration of 30 months, completed in October 2023.

The Center supports applied research, pilot-scale experimentation, and technology demonstration. The methodological framework combines field surveys, laboratory experiments, pilot-scale systems, material flow analysis, and environmental performance assessment tools. Emphasis is placed on the integration of scientific research with regional development priorities.

Aegean_BIOECONOMY provides a collaborative platform for research, technological innovation, education, and regional planning aligned with environmental legislation and sustainability goals. It bridges academic research with applied solutions that foster economic resilience, job creation, and sustainable development in island economies. The overall objective is the adoption of the EU Bioeconomy Strategy making sure it reflects the specific conditions of the island regions. This can lead to new jobs, contribution to achieve carbon neutrality, shift to the circular economy model, harnessing of healthy natural ecosystem as well as modernisation and strengthening industry.

Research areas

Aegean_BIOECONOMY is organized into four interlinked research themes that address priority needs for circular bioeconomy implementation in insular contexts. It is important to highlight that a core output of the project was the development of permanent research infrastructure — digital platforms, pilot-scale units, and laboratory tools that enable continuous experimentation and support collaboration with regional stakeholders. The research areas are categorized as:

- BIOMass — Sustainable Production and Management of Biomass
- Nature4Water — Sustainable Water and Soil Management
- REproduct — Recycling and Creation of New Materials
- Hotel Footprinting — Tourism Environmental Footprint Reduction

Regional engagement and stakeholder integration

Aegean_BIOECONOMY engages regional and local stakeholders — including SMEs, policymakers, community organizations, and tourism operators — to foster knowledge exchange and co-creation of sustainable solutions. Training programs, workshops, and events (e.g., spring schools on circular bioeconomy) enhance regional capacity and encourage adoption of innovative practices.

Selected case studies for the sustainable management of biomass

Arthrospira (Spirulina) platensis cultivation using cheese whey

Introduction and scope of the study

Biological processes, and especially biotechnology-based solutions, play a central role in the transition to circular economy by enabling the conversion of organic residues into high-value products while reducing environmental impacts (Vaitsis et al., 2022).

Previous studies have demonstrated the feasibility of cultivating *A. platensis* under mixotrophic conditions using dairy effluents, highlighting the potential for simultaneous biomass production and wastewater treatment (Pereira et al., 2019; Papadopoulos et al., 2022). However, important knowledge gaps remain regarding the influence of operational parameters such as substrate concentration, pH and illumination regime on biomass productivity and nutrient removal efficiency. Moreover, many existing studies rely on sterilized or extensively pretreated waste streams, limiting their applicability to real-world circular economy implementations. Addressing these gaps is essential for advancing *Arthrospira*-based systems from laboratory-scale investigations toward practical, sustainable applications.

The present study evaluates the cultivation of *Arthrospira* (*Spirulina*) *platensis* strain PCC8005 using diluted, non-sterile cheese whey as a nutrient source, aiming to partially substitute conventional synthetic growth media. Batch experiments were conducted to investigate the combined effects of cheese whey concentration, pH and illumination regime on biomass production, nutrient uptake and organic matter removal.

Specifically, the objectives were to assess the growth performance of *A. platensis* in whey-based media under alkaline conditions and compare biomass productivity under continuous illumination and light/dark photoperiods. The removal of parameters such as

chemical oxygen demand, nitrogen and phosphorus was determined and the operational conditions that optimize both biomass yield and treatment efficiency were identified.

By focusing on non-aseptic conditions and minimal pre-treatment requirements, the study seeks to provide results that are directly transferable to low-cost, decentralized and regionally adapted applications.

This work contributes to circular economy principles by demonstrating a biological pathway for the simultaneous treatment and valorization of cheese whey, a major by-product of the dairy industry. The cultivation of *Arthrospira platensis* enables the recovery of nutrients and organic carbon from cheese whey and their conversion into valuable microbial biomass, effectively closing material loops within the agri-food system (Abreu et al., 2012; Lafarga et al., 2021).

The proposed approach supports circular economy objectives through:

- Resource recovery, by transforming nitrogen, phosphorus and organic carbon into biomass rather than disposing of them as waste;
- Waste reduction, achieved through high COD and nutrient removal efficiencies, mitigating the environmental footprint of dairy effluents;
- Economic sustainability, enabled by the use of non-sterile substrates and the inherent robustness of *A. platensis* under alkaline conditions;
- Value creation, as the produced biomass can serve as a feedstock for bioenergy, biofertilizers or other bioproducts, extending the value chain beyond wastewater treatment (Mitra & Mishra, 2019).

Overall, the findings support the integration of microalgal biotechnology into sustainable waste management strategies and reinforce the role of *Arthrospira platensis* cultivation as a viable circular economy solution for the dairy sector.

Materials and methods

Microorganism and maintenance conditions

The cyanobacterium *Arthrospira (Spirulina) platensis* strain PCC8005 (Institut Pasteur, France) was used in this study. Stock cultures were maintained at the Waste Management Laboratory of the University of the Aegean in Erlenmeyer flasks containing Cogne-modified Zarrouk medium (CMZM) (Cogne et al., 2003). Cultures were incubated at 28 °C under continuous illumination provided by an 8 W LED light source (680 lm).

The CMZM contained (g L⁻¹): NaCl (1.0), CaCl₂ (0.03), K₂SO₄ (1.0), MgSO₄·7H₂O (0.08), K₂HPO₄ (0.5), NaNO₃ (2.5), NaHCO₃ (10.5), Na₂CO₃ (7.6), EDTA (0.08) and FeSO₄·7H₂O (0.01). Trace elements were supplied according to Cogne et al. (2003). Cultures used as inoculum were harvested during the exponential growth phase.

Cheese whey origin and pretreatment

Cheese whey was obtained from a local dairy processing unit located on Lesbos Island (Greece). The physicochemical properties of the whey were characterized by high organic content and acidic pH, reflecting typical dairy by-product composition (pH equal to 3.62 and COD value of 62.334 mg/L). Whey samples were stored at -20 °C until use.

Prior to cultivation experiments, cheese whey was centrifuged at 1500 rpm for 15 min and subsequently filtered through 1 µm filters to remove coarse suspended solids. This mild pretreatment aimed to reduce turbidity and facilitate light penetration while maintaining the non-sterile nature of the substrate, as previously suggested by Pereira et al. (2019).

Experimental design and cultivation conditions

Batch experiments were conducted in 250 mL Erlenmeyer flasks containing 130 mL of growth medium. Cheese whey was diluted with tap water to final concentrations of 2.5%, 5% and 10% (v/v). A whey concentration of 20% (v/v) was initially tested but excluded due to growth inhibition, in agreement with previous findings (Pereira et al., 2019).

Each flask was inoculated with 20 mL of *A. platensis* culture. Cultivation was performed at 28 °C for 14 days under two illumination regimes: (i) continuous illumination using fluorescent lamps (OSRAM FQ 39 W/840 HO), and (ii) a 12 h light/12 h dark photoperiod. Experiments were carried out at pH values of 8.5, 9.5 and 10.5. All trials were performed in triplicate. Zarrouk medium cultures served as controls.

Analytical methods

Growth was monitored by measuring optical density at 750 nm every two days. Biomass concentration was quantified as volatile suspended solids (VSS). Samples were filtered through 1 µm glass fiber filters, dried at 105 °C for 24 h and weighed. Subsequently, filters were combusted at 550 °C for 30 min to determine volatile solids content.

Chemical oxygen demand (COD), total nitrogen (TN), nitrate nitrogen (NO_3^- -N) and phosphate (PO_4^{3-} -P) concentrations were determined spectrophotometrically using Hach standard test kits.

Results and Discussion

Acclimation to whey-based media

All cultures exhibited a short acclimation period during the first 24 h following inoculation, reflecting metabolic adjustment to the complex organic substrate. Similar acclimation behavior has been reported for cyanobacteria cultivated on waste-derived media (Abreu et al., 2012; Pereira et al., 2019).

Growth under continuous illumination

Biomass production under continuous illumination increased with both whey concentration and pH. The highest biomass yield ($0.76 \text{ g L}^{-1} \text{ VSS}$) was obtained at pH 9.5 using 10% (v/v) whey. Cultures maintained at pH 8.5 exhibited significantly lower growth, confirming the preference of *A. platensis* for alkaline environments (Ogbonda et al., 2007; Papadopoulos et al., 2022).

Nitrogen uptake was enhanced at higher pH values, with maximum NO_3^- -N consumption observed at pH 10.5. Phosphate removal was nearly complete at lower whey concentrations, whereas partial removal was recorded at 10% (v/v), likely due to increased initial phosphorus loading.

COD removal exceeded 80% in most treatments, demonstrating effective organic matter utilization even in non-sterile conditions, consistent with previous studies on wastewater based *Arthrospira* cultivation (Calicioglu & Demirer, 2022).

Growth under light/dark cycles

Cultivation under a 12 h light/dark regime resulted in superior biomass production compared to continuous illumination. The highest biomass concentration of the study ($\approx 1.04 \text{ g L}^{-1} \text{ VSS}$) was achieved at pH 10.5 with 10% (v/v) whey. Enhanced growth under photoperiodic illumination has been attributed to improved photosynthetic efficiency and reduced photoinhibition (Marquez et al., 1993; Chen & Zhang, 1997).

Nitrogen removal under light/dark conditions was more pronounced, with near-complete nitrate depletion observed at pH 10.5. COD removal reached up to 85%, confirming the dual function of *A. platensis* cultivation as biomass production and wastewater treatment.

Table 1: Consumption of nutrients, COD removal and determination of VSS, during *Arthrospira platensis* growth using cheese whey. Cultures with continuous illumination and dark/light cycles. Values presented were measured in the first and last day of the trials

	Cheese Whey Concentration % (v/v)	Continuous illumination						Light/dark cycles			
		Experiment 1 pH=8.5		Experiment 2 pH=9.5		Experiment 3 pH=10.5		Experiment 4 pH=8.5		Experiment 5 pH=10.5	
TN (mg/L)		t0	t14	t0	t14	t0	t14	t0	t14	t0	t14
	2.50%	84	69	86	39	86	38	84	22	86	30
	5%	101	82	106	63	106	46	101	37	106	40
	10%	238	119	130	92	130	90	157	62	130	55
NO ₃ ⁻ N (mg/L)											
	2.50%	55	42	50	29	50	22	55	17	50	0.6
	5%	57	23	55	24	55	20	57	13	55	0.8
	10%	65	34	61	16	61	20	65	0.7	61	0.7
COD (mg/L)											
	2.50%	1135	0	1000	0	1000	0	1135	0	1000	63
	5%	1860	364	1580	221	1580	149	1860	85	1580	248
	10%	5210	974	4080	986	4080	973	5210	117	4080	535
PO ₄ ³⁻ (mg/L)											
	2.50%	6.1	<2	6.4	<2	6.4	<2	11.5	13.7	6.4	6.9
	5%	11.2	<2	11	<2	11.0	<2	14.0	14.7	11.0	11.4
	10%	23.8	19.7	28	17.9	28.0	17	23.8	20.2	28.0	18.1
VSS (g/L)											
	2.50%	0.16	0.18	0.16	0.33	0.16	0.29	0.12	0.60	0.12	0.74
	5%	0.16	0.22	0.16	0.46	0.16	0.50	0.11	0.63	0.11	0.97
	10%	0.12	0.28	0.12	0.76	0.12	0.71	0.14	0.65	0.14	1.04

Comparative assessment

Light/dark cycles combined with alkaline pH conditions favored biomass productivity and nutrient uptake. Even at low whey concentrations, photoperiodic illumination outperformed continuous lighting. These findings support the feasibility of integrating *A. platensis* cultivation into circular economy schemes for dairy wastewater valorization (Vaitis et al., 2022). In Table 1, the consumption of nutrients, COD removal and determination of VSS in cultures with continuous illumination and dark/light cycles are presented.

The investigation of the production of Polyhydroxyalkanoate (PHA) bioplastics of consistent composition using organic waste

The use of organic waste streams as feedstocks for PHA production represents a key pathway toward sustainable and economically viable bioplastics. Organic waste and waste-derived volatile fatty acids provide low-cost carbon sources while simultaneously addressing waste management challenges, thereby aligning PHA production with circular bioeconomy principles (Ntaikou et al., 2014). In this context, mixed microbial cultures (MMCs) offer significant advantages over pure cultures, as they can operate under non-sterile conditions and tolerate variable substrate compositions, reducing operational complexity and costs (Serafim et al., 2008; Kourmentza et al., 2017). Feast–famine operational strategies selectively enrich PHA-accumulating microorganisms, enhancing process robustness and storage capacity. Overall, bioplastics production from organic waste supports sustainable biomass management by converting residual carbon into value-added materials, contributing to waste reduction,

material circularity and climate mitigation—benefits that are particularly relevant for insular and resource-constrained regions supporting the green transition.

Mixed Microbial Cultures (MMCs) have been tested extensively to produce PHAs due to their potential in reducing costs both by utilizing organic waste as feedstock and by minimizing aseptic conditions. Replacing single-use petrochemical plastics with materials manufactured using organic wastes could be a significant step in the advancement of circular economy. Optimization of MMC enrichment in PHA producing microorganisms is crucial for the maximization of PHA production.

The use of MMCs can reduce the production costs as aseptic conditions are not required for the whole process. A simplified method of producing PHA bioplastics from synthetic medium and organic waste, is developed to be able to qualitatively test parameters that control the composition of PHA bioplastics and the productivity of the process.

Materials and Methods

Inoculum and reactor setup

Draw-fill reactors were used using 3.5 days cycles and Sludge Retention Time (SRT) of 7 days to simplify the enrichment procedure. The biomass was enriched with microorganisms in concentrations of 50 and 83 mmol/day. Growth conditions with and without aeration were tested. Accumulation of PHA bioplastics was also carried out using Draw-and-Fill reactors (DFR) with the enriched biomass to obtain product above 40% by weight of cell mass. The production was validated gravimetrically and qualitatively with Nile Red microscopy. Extraction with chloroform was performed to obtain films. COD, VFA and ammonia measurements were performed to elucidate the process. Biomass growth in concentrations over 2.5 was achieved using 83 Cmmol/day, while growth using 50 Cmmol/day was insignificant. Aeration was found to be imperative for growth.

Feeding regime and operational strategy

The enrichment strategy was based on long operational cycles (two cycles per week) and alternating feast–famine conditions. At the start of each cycle, the reactor was fed with a synthetic medium containing acetate and propionate as volatile fatty acid (VFA) carbon sources and ammonia as the nitrogen source.

The point of this long-cycle method is to produce PHAs viably without automatic feed systems. The method relies on alternating periods of feast and famine. A DFR, (draw and fill reactor - Figure 2) was used to feed activated sludge with Volatile Fatty Acids (VFAs) in this case mixtures of acetate and propionate as a source of Carbon and ammonia as a source of nitrogen in the beginning of the cycle. A famine period of at least 5 times the feast period favors the growth of Mixed Microbial Cultures (MMCs) able to store PHA granules as a source of carbon (Figure 3).



Figure 2. Draw and Fill reactor used

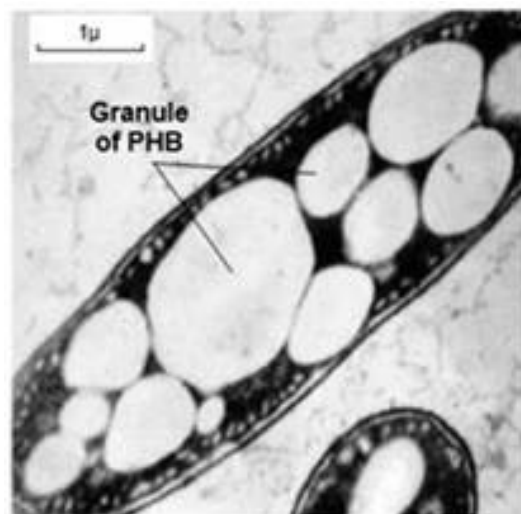


Figure 3. Transmission electron micrograph of granules of PHB in microorganisms (Lenz and Marchessault 2005)

Organic loading rates (OLR) of 42.9 and 71.4 Cmmol d⁻¹ were applied to assess their influence on microbial enrichment and system performance. Famine periods were maintained at least five times longer than feast periods, favoring microorganisms capable of intracellular PHA storage (Bengtsson et al., 2017).

Monitoring and accumulation experiments

Biomass evolution during enrichment was monitored by measuring volatile suspended solids (VSS). Following selected enrichment cycles, accumulation experiments were conducted by supplying carbon without nitrogen, thereby suppressing biomass growth and promoting PHA storage.

Chemical oxygen demand (COD) and ammonia concentrations were measured to confirm substrate consumption and nutrient limitation. During accumulation phases, increases in VSS were assumed to be predominantly associated with intracellular PHA accumulation.

Results and Discussion

Enrichment performance at low organic loading

At an OLR of 42.9 Cmmol d⁻¹, microbial growth peaked approximately 1.5 days into the cycle. Prolonged aeration resulted in increased medium viscosity and slime formation, which impeded oxygen transfer. Such behavior is commonly associated with nitrogen limitation and extracellular polymeric substance (EPS) production (Silva et al., 2017).

Effect of increased organic loading

Increasing the OLR to 71.4 Cmmol d⁻¹ delayed the growth peak, indicating improved substrate availability. However, slime formation and aeration limitations persisted, suggesting that long-cycle operation under nitrogen-limited conditions inherently promotes EPS production.

PHA accumulation potential

After eight enrichment cycles at the higher OLR, accumulation experiments demonstrated significant polymer storage. VSS increased by 39.7% after 23 h and by 47% after 32 h, indicating effective PHA accumulation. These results confirm that the enriched MMCs were capable of storing carbon intracellularly when growth was restricted. VSS monitoring in the enrichment phase and in the production stage is presented in Figures 4a and 4b.

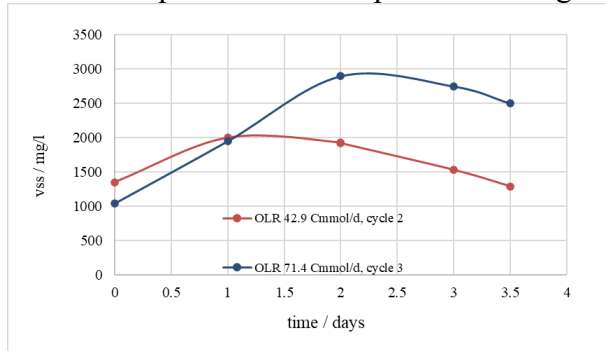


Figure 4a. VSS monitoring in the enrichment stage

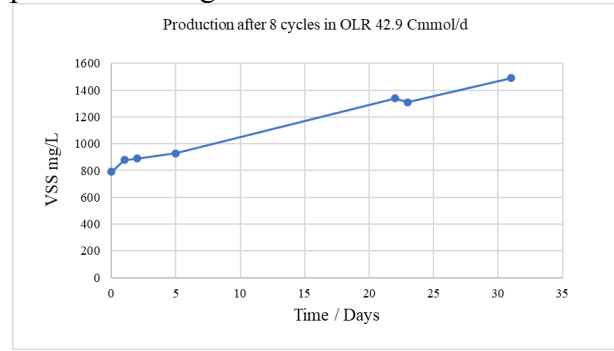


Figure 4b. VSS monitoring in the production stage

Substrate utilization dynamics

COD and ammonia were rapidly depleted within the first day of the cycle at lower OLR, confirming the establishment of clear feast–famine conditions. Rapid nitrogen depletion likely contributed both to PHA accumulation and EPS release, highlighting the need for careful nutrient management in long-cycle systems.

Process implications

The results demonstrate that PHA production using long-cycle operation is feasible without automated feeding. However, excessive slime formation presents a critical operational challenge. Future optimization should focus on shorter cycles, improved nutrient control and gradual transition to real organic waste streams, in line with circular bioeconomy principles (Ntaikou et al., 2018; Bengtsson et al., 2017).

Conclusions

The Center for Sustainable Circular Bioeconomy and Energy represents a model of how research infrastructures can catalyse transition to a circular bioeconomy in insular and geographically dispersed regions. By bridging multidisciplinary science, stakeholder engagement, and applied innovation, it contributes to sustainable development aligned with global and European green transition agendas.

The study demonstrates that circular bioeconomy strategies can effectively support the green transition of insular regions. By integrating biomass valorization, renewable energy production, nature-based solutions, material recovery, and environmental footprint assessment, island territories can enhance resource efficiency while protecting fragile ecosystems. The presented approach provides a replicable model for other insular and remote regions pursuing sustainable development pathways.

This study demonstrates the pivotal role that targeted research infrastructures can play in accelerating the transition toward a circular bioeconomy in insular and resource-constrained regions. Through the activities of the Center for Sustainable Circular Bioeconomy and Energy (Aegean_BIOECONOMY), an integrated framework was developed that combines applied research, pilot-scale experimentation and stakeholder engagement to address critical

challenges related to biomass management, waste valorization and environmental sustainability.

The selected case studies highlight the feasibility and effectiveness of biological approaches for closing material loops within island agri-food systems. The cultivation of *Arthrospira* (*Spirulina*) *platensis* on cheese whey demonstrated that a problematic dairy by-product can be simultaneously treated and valorized under non-sterile conditions, achieving substantial biomass production and high removal efficiencies for organic matter and nutrients. The results confirm that alkaline pH and photoperiodic illumination enhance both biomass productivity and wastewater treatment performance, reinforcing the suitability of *A. platensis* for decentralized applications in island environments. This approach supports resource recovery, reduces environmental pressures associated with whey disposal and creates opportunities for value-added bioproducts.

In parallel, the investigation of polyhydroxyalkanoate (PHA) production using mixed microbial cultures illustrated the potential of converting organic carbon into biodegradable bioplastics through cost-efficient enrichment and accumulation strategies. Although operational challenges such as excessive slime formation were identified, the results confirmed that long-cycle feast–famine regimes can enrich PHA-storing microorganisms and achieve significant intracellular polymer accumulation. These findings underline the importance of operational optimization and nutrient management to improve process stability and scalability, particularly when transitioning from synthetic substrates to real organic waste streams.

Beyond the technical outcomes, the study emphasizes the broader contribution of circular bioeconomy interventions to regional development. By integrating biomass valorization, renewable materials production, nature-based solutions and environmental footprint assessment, the Aegean_BIOECONOMY initiative provides a replicable model for strengthening local value chains, reducing dependence on imported resources and enhancing environmental resilience in island territories. The engagement of regional stakeholders further supports knowledge transfer and facilitates the uptake of sustainable practices aligned with European Green Deal and bioeconomy strategies.

Overall, the results confirm that circular bioeconomy strategies, when supported by dedicated research infrastructures and region-specific implementation frameworks, can significantly contribute to the green transition of insular regions. Future efforts should focus on scaling up pilot applications, integrating multiple valorization pathways and strengthening policy–science–industry linkages to maximize environmental, economic and social benefits.

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