BioCircular Port Models for Sustainable Trade vis-à-vis Maritime Risks: Integrating Regenerative Ecosystems and Circular Technologies

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Abstract:

This research paper explores the conceptual framework and practical implications of "BioCircular Ports" as a transformative solution for the post-carbon era of international trade. Moving beyond conventional notions of sustainability, BioCircular Ports are envisioned as closed-loop ecosystems that integrate advanced bio-technologies and circular economy principles to minimize environmental impact while maximizing resource efficiency. Key features include integrated aquaponics for local food production, advanced rainwater harvesting and greywater recycling systems for water self-sufficiency, and on-site manufacturing of ship parts from recycled ocean plastics using 3D printing technologies. This paper discusses the potential for BioCircular Ports to revolutionize maritime logistics, reduce carbon footprints, enhance resilience, and create new economic opportunities. Through a detailed literature review, a proposed research methodology, and a discussion of potential challenges and future research directions, this paper aims to lay the groundwork for the development and implementation of these innovative port models.

Imagine ports as closed-loop ecosystems—integrating aquaponics, rainwater harvesting, and 3D-printed ship parts from recycled ocean plastic.

Keywords: BioCircular Ports, Post-Carbon Trade, Circular Economy, Aquaponics, Rainwater Harvesting, 3D Printing, Ocean Plastic, Maritime Logistics, Sustainable Ports.

Introduction:

The global maritime industry, the backbone of international trade, faces an unprecedented imperative to decarbonize and transition towards sustainable practices. Traditional linear economic models, characterized by resource depletion and waste generation, are no longer viable in an era defined by climate change, resource scarcity, and increasing environmental regulations. This paper introduces the concept of "BioCircular Ports" as a paradigm shift in port development and operation, envisioning them not merely as logistical hubs, but as self-sustaining, closed-loop ecosystems that actively contribute to environmental regeneration and resource optimization.

The theory behind BioCircular Ports draws heavily from the principles of the circular economy, which advocates for the elimination of waste and continuous use of resources. Applied to a port context, this translates into designing systems where waste from one process becomes a valuable input for another. For instance, organic waste from port operations or ships could feed anaerobic digesters, producing biogas for energy, while nutrient-rich wastewater from aquaponics could be treated and reused for irrigation. The integration of biotechnology, such as advanced bioremediation techniques and algae cultivation, further enhances their ecological footprint.

Beyond their environmental benefits, BioCircular Ports offer significant practical advantages. They enhance a port's resilience to external shocks, such as water shortages or supply chain disruptions, by fostering self-sufficiency. They also create new economic opportunities through the development of green industries, local food production, and the valorization of waste streams.

This introduction will also delve into key aspects of maritime law and practice that underpin international trade, providing essential context for understanding the operational environment of BioCircular Ports.

- **Maritime Disputes:** International trade often gives rise to complex disputes, ranging from cargo damage and collision claims to charter party disagreements and salvage remuneration. These disputes necessitate efficient and equitable resolution mechanisms.
- **Arbitration:** Maritime arbitration has emerged as a preferred method for resolving international maritime disputes due to its flexibility, confidentiality, and the specialized expertise of arbitrators. Major arbitration centers like London, Singapore, and New York play a crucial role in facilitating these resolutions, offering a streamlined alternative to traditional court litigation. The enforceability of arbitral awards under international conventions like the New York Convention further strengthens its appeal.
- **General Average:** A unique principle in maritime law, General Average applies when extraordinary sacrifices or expenses are voluntarily incurred to save a common maritime adventure (ship and cargo) from a peril. In such cases, all parties with an interest in the adventure contribute proportionally to the losses. This ancient principle, codified in the York-Antwerp Rules, ensures fairness and encourages cooperation in times of crisis at sea.
- **Salvage:** Salvage refers to the voluntary and successful saving of property at peril at sea. Salvors are entitled to a reward for their efforts, calculated based on factors like the value of the property saved, the degree of danger, and the skill and efforts of the salvors. The concept of "no cure, no pay" is fundamental to salvage law, meaning a salvor is only rewarded if their efforts are successful.
- **Suez Canal and other Main Routes of International Trade:** The Suez Canal, a vital man-made waterway, significantly shortens trade routes between Europe and Asia, demonstrating the critical importance of strategic maritime choke points. Other main routes include the Panama Canal (connecting the Atlantic and Pacific), the Strait of Malacca (between the Indian and Pacific Oceans), and major shipping lanes across the Atlantic and Pacific. These routes are the arteries of global trade, and their efficiency and security are paramount. The concept of BioCircular Ports, with their focus on sustainability and resilience, can contribute to the long-term viability and environmental integrity of these crucial trade corridors.

The confluence of environmental imperatives and the established complexities of maritime trade necessitates a radical rethinking of port infrastructure and operations. BioCircular Ports offer a holistic vision for a sustainable and resilient future for international commerce.

Literature Review:

The concept of sustainable ports has gained significant traction in academic and industry discussions over the past two decades. Early literature focused on mitigating the environmental impact of port operations, including air pollution from ship emissions, water pollution from oil spills and ballast water, and habitat destruction from dredging and land reclamation. Works by authors such as Lam and Notteboom (2014) and Acciaro et al. (2014) highlighted the importance of environmental management systems and corporate social responsibility in port operations.

More recently, the discourse has shifted towards the circular economy, with increasing recognition of its potential to transform various industries, including logistics and maritime transport. Ghisellini et al. (2016) provided a comprehensive overview of circular economy principles and their application. Studies on waste valorization and industrial symbiosis in port areas have also emerged, exploring how waste streams from one industry can become resources for another (e.g., Pan et al., 2017).

Specific technologies relevant to BioCircular Ports have also been explored independently. Research on aquaponics systems, their efficiency in water and nutrient use, and their potential for urban and industrial food production is extensive (e.g., Rakocy et al., 2006; Tyson et al., 2011). Similarly, rainwater harvesting and greywater recycling technologies have been widely studied for their potential to enhance water security in various contexts (e.g., Farreny et al., 2011; Domènech and Saurí, 2010). The advent of additive manufacturing (3D printing) has opened new avenues for on-demand production and resource efficiency, with a growing body of literature on its applications in various industries, including the potential for recycling plastics (e.g., Huang et al., 2012; Vayre et al., 2012). While research on individual components is robust, the integrated application of these technologies within a holistic "BioCircular Port" framework remains an area requiring significant further exploration.

The concept of post-carbon trade is still nascent, but it builds upon the broader discussions of decarbonization within the shipping industry (e.g., IMO's efforts towards greenhouse gas emission reduction). The integration of renewable energy sources in ports (e.g., solar, wind) has been examined (e.g., Cristea et al., 2013), but a complete systems approach that encompasses resource loops, localized production, and novel material streams like recycled ocean plastic for ship components is less explored. This paper aims to bridge this gap by synthesizing existing knowledge on sustainable technologies and circular economy principles within the specific context of port operations, pushing the boundaries towards a truly regenerative model for maritime trade.

Research Methodology:

This research will employ a multi-faceted methodology combining conceptual development, case study analysis, and scenario planning to explore the feasibility and benefits of BioCircular Ports.

1. **Conceptual Framework Development:**
    - **Literature Synthesis:** A comprehensive review of existing literature on sustainable port practices, circular economy principles, aquaponics, rainwater harvesting, 3D

printing with recycled materials, and related biotechnologies will form the foundation.
    - **Systems Thinking Approach:** The interdependencies and feedback loops between various BioCircular Port components (e.g., waste-to-energy, water recycling, localized production) will be mapped and analyzed to understand their holistic impact.
    - **Stakeholder Identification:** Key stakeholders, including port authorities, shipping companies, logistics providers, technology developers, local communities, and regulatory bodies, will be identified to understand their potential roles and interests.
2. **Case Study Analysis (Hypothetical/Precedent-Based):**
    - Given the nascent nature of fully integrated BioCircular Ports, this section will involve analyzing existing port initiatives that embody *elements* of the BioCircular concept. For example, a port with significant renewable energy integration, a city with a robust circular economy initiative, or a community with successful large-scale aquaponics operations.
    - **Comparative Analysis:** By examining these fragmented examples, we will identify best practices, challenges, and transferable lessons relevant to a complete BioCircular Port model.
    - **Data Collection (from existing reports/studies):** Data on resource consumption, waste generation, economic benefits, and environmental impacts from these precedent cases will be analyzed to inform the BioCircular Port model.
3. **Scenario Planning:**
    - **Development of BioCircular Port Scenarios:** Multiple scenarios for the implementation of BioCircular Ports will be developed, varying in terms of scale, technological adoption, and policy support.
    - **Impact Assessment (Qualitative and Quantitative where possible):** For each scenario, the potential impacts on environmental sustainability (carbon emissions reduction, waste diversion, water conservation), economic viability (job creation, cost savings, new revenue streams), and social benefits (local food security, community engagement) will be assessed. This will involve qualitative reasoning supported by estimations based on existing technological capabilities.
    - **Risk and Opportunity Analysis:** Potential risks (e.g., technological immaturity, regulatory hurdles, investment costs) and opportunities (e.g., market differentiation, enhanced resilience, new business models) associated with BioCircular Ports will be identified and evaluated.
4. **Feasibility Assessment (Conceptual):**
    - Based on the preceding steps, a conceptual feasibility assessment will be conducted, evaluating the technical, economic, environmental, and social viability of implementing BioCircular Ports. This will involve identifying critical success factors and potential barriers.

Limitations:

This research paper is primarily conceptual and theoretical, aiming to lay the groundwork for a novel port model. As such, it has several limitations:

- **Lack of Empirical Data on Fully Integrated BioCircular Ports:** To date, no port fully embodies all the integrated features of a BioCircular Port as described in this paper. Therefore, the analysis relies heavily on theoretical frameworks, existing technologies applied in isolation, and hypothetical scenarios.
- **Assumptions on Technological Maturity and Cost-Effectiveness:** While the individual technologies (aquaponics, 3D printing, rainwater harvesting) are mature, their seamless integration at a port scale, and the precise cost-benefit analysis of such an integrated system, require further detailed engineering and economic modeling, which is beyond the scope of this paper.
- **Regulatory and Policy Frameworks:** The current international and national regulatory frameworks for maritime trade and port operations may not be fully aligned with the requirements of BioCircular Ports, potentially posing significant implementation challenges that are not exhaustively detailed here.
- **Social and Community Acceptance:** The successful implementation of BioCircular Ports would require significant engagement and acceptance from local communities and port stakeholders. This research provides a high-level overview but does not delve into a detailed sociological analysis of potential resistance or facilitation.
- **Dynamic Nature of Technology and Policy:** The pace of technological innovation and policy development is rapid. The assessments made in this paper are based on current understanding and may need to be updated as new advancements emerge.
- **Specific Geographic and Climatic Considerations:** The optimal design and implementation of BioCircular Ports would be highly dependent on the specific geographic location, climate, and existing infrastructure of a port. This paper provides a general framework, but detailed regional analyses are needed for practical application.

Future Research Lead:

The development of BioCircular Ports opens up numerous avenues for future research, transitioning from conceptualization to practical implementation and optimization:

- **Detailed Techno-Economic Feasibility Studies:** Conducting in-depth engineering and economic analyses for specific BioCircular Port components and their integration, including life cycle cost assessments, return on investment (ROI) calculations, and optimization models for resource flows.
- **Pilot Projects and Demonstrators:** Developing and implementing small-scale pilot projects within existing ports to test the viability of integrated BioCircular systems, gather empirical data, and identify practical challenges.
- **Development of Policy and Regulatory Frameworks:** Researching and proposing new national and international policies, regulations, and incentives that would facilitate the adoption and operation of BioCircular Ports, including legal frameworks for resource ownership and waste valorization.

- **Supply Chain Integration and Optimization:** Investigating how BioCircular Ports can be seamlessly integrated into existing global supply chains, exploring new logistics models, and assessing the impact on shipping routes and transit times.
- **Material Science and 3D Printing Advancements:** Further research into the development of advanced sustainable materials from recycled ocean plastics suitable for marine applications, and optimization of 3D printing technologies for large-scale, high-strength marine components.
- **Social and Behavioral Aspects:** Studying the social acceptance of BioCircular Ports by local communities, port workers, and shipping companies, including potential job creation, skill requirements, and community engagement strategies.
- **Environmental Impact Assessment (LCA):** Conducting comprehensive cradle-to-grave Life Cycle Assessments (LCAs) of BioCircular Ports compared to conventional ports to quantify their full environmental benefits and identify potential trade-offs.
- **Renewable Energy Integration and Smart Grids:** Deep dive into the optimal integration of various renewable energy sources within BioCircular Ports and the development of smart grid systems for energy self-sufficiency and resilience.
- **Water Management Systems Optimization:** Advanced research into optimizing water harvesting, treatment, and recycling systems within ports, including the potential for desalination powered by renewable energy.
- **Bio-sequestration and Ecosystem Restoration:** Exploring the potential of BioCircular Ports to actively contribute to local ecosystem restoration and carbon sequestration through innovative biological solutions.

Discussion:

The vision of BioCircular Ports represents a radical departure from the traditional port model, driven by the urgent need for decarbonization and resource efficiency in global trade. The integration of aquaponics, rainwater harvesting, and 3D-printed ship parts from recycled ocean plastic offers a synergistic approach to address multiple environmental and economic challenges simultaneously.

Aquaponics within port areas can provide a localized, sustainable food source, reducing reliance on long-distance food transportation and enhancing food security for port communities and even potentially provisioning visiting vessels. This also creates a closed-loop nutrient system, minimizing waste. Rainwater harvesting and greywater recycling systems can significantly reduce a port's freshwater footprint, a critical factor in regions facing water scarcity. This self-sufficiency enhances operational resilience and reduces dependence on municipal water supplies.

The most innovative aspect lies in the on-site 3D printing of ship parts from recycled ocean plastic. This not only addresses the pervasive problem of marine plastic pollution by valorizing a waste stream, but also offers significant logistical and environmental benefits. Producing parts on-demand, close to where they are needed, reduces the need for extensive global supply chains for spares, cutting down on transportation emissions and lead times. It also promotes a localized manufacturing ecosystem within the port, fostering innovation and creating new skilled jobs. The ability to repair and replace components quickly and locally can significantly reduce downtime for ships, improving operational efficiency.

However, the realization of BioCircular Ports is not without its challenges. Significant upfront investment would be required for infrastructure development, technology integration, and workforce training. Regulatory frameworks would need to adapt to accommodate these new operational models, particularly concerning waste streams and localized manufacturing. The scalability of these technologies, particularly the volume of recycled ocean plastic needed for widespread ship part production, also requires careful consideration. Furthermore, the quality and durability of 3D-printed parts for critical ship components would need rigorous testing and certification to meet stringent maritime safety standards.

Despite these hurdles, the long-term benefits are substantial. BioCircular Ports offer a compelling pathway to a truly sustainable maritime industry, moving beyond merely mitigating negative impacts to actively creating positive environmental and social value. They represent an opportunity to transform ports from sources of pollution to hubs of innovation, resource regeneration, and green economic growth.

Risk and Revenue Management in Maritime Industries

In conventional port logistics, maritime risk encompasses operational delays, ecological degradation, supply chain disruptions, and human resource vulnerabilities. Geopolitical instability, unpredictable weather patterns, and aging infrastructure all amplify exposure to loss. However, when viewed through the lens of **BioCircular Port Models**, these risks take on new dimensions. The transition to regenerative ecosystems—such as rainwater harvesting, aquaponics integration, and recycled materials manufacturing—introduces system-level resilience but also invites uncertainty in implementation. Stakeholders must assess ecological balance, material inputs, and regulatory alignment to avoid unintended disruptions. For instance, aquaponic systems may be sensitive to port industrial emissions, while the effectiveness of ocean-plastic repurposing hinges on reliable sorting, supply consistency, and scalable 3D printing capabilities.

Moreover, the circular design ethos challenges traditional revenue-risk models by shifting value generation from throughput maximization to ecosystem co-performance. Ports that prioritize regeneration must navigate new categories of risk—including biosecurity controls, ecosystem management liability, and green technology obsolescence. Human resource considerations evolve as well: seafarers interacting with biogenic port systems require updated training, and prolonged deployment in hybrid green ports may introduce stress due to culture shock, skill mismatches, or sensory adaptation. Ultimately, **BioCircular Ports** offer a strategic hedge against long-term climate and resource volatility—but only if their governance frameworks actively address emerging ecological, technological, and human factors.

The maritime sector—responsible for transporting over 80% of global trade—operates under complex, volatile conditions. Effective risk and revenue management is paramount to ensuring profitability, continuity, and resilience.

Volatility and Geopolitical Disruptions

Maritime operations are exposed to unpredictable geopolitical forces. Ongoing conflicts in the Red Sea, the Russia-Ukraine war, and rising tensions in the South China Sea directly disrupt trade routes and raise insurance premiums. Sanctions, port access restrictions, and embargoes can shift demand overnight, forcing rerouting and demurrage losses. Risk managers must continuously monitor maritime chokepoints and anticipate regional instability to adapt vessel deployment and pricing strategies.

Technology Shifts and Operational Uncertainty

Digitalization and automation introduce both efficiency and cyber vulnerabilities. Blockchain systems for cargo traceability, AI-driven routing, and port-side robotics reduce costs—but create exposure to hacking, data breaches, and system dependencies. The race toward greener fuels and smart port ecosystems further adds to capital expenditure risks, making ROI forecasting more complex.

Revenue Complexity amid High Volume and Extended Cycles

Revenue management in shipping requires navigating long asset lifecycles, high cargo volumes, and price-sensitive markets. Container throughput and bulk commodity rates are influenced by global GDP, climate events, and fleet supply. Longer voyage durations due to re-routing (as seen in post-Suez scenarios) inflate costs, challenge scheduling algorithms, and delay revenue recognition.

Climate Variability and Crew Health Risks

Maritime operations span extreme climatic zones—from Arctic voyages to equatorial passages—resulting in vessel wear, unpredictable weather risks, and crew health concerns. Sea sickness, tropical diseases, and fatigue from operating in volatile conditions contribute to HR challenges and insurance claims.

Human Resource Management at Sea

Crew members face prolonged periods away from home, leading to homesickness, isolation, and burnout. Retention suffers due to limited career progression and constant travel. Updating technical skills to match automation trends—such as digital navigation systems and remote diagnostics—is difficult during deployment. Shore-leave restrictions and limited access to mental health support amplify stress. A robust HR strategy must include rotation planning, digital learning platforms, and onboard wellness initiatives.

These interwoven risks demand a dynamic approach—balancing agility with long-term investment. Modern maritime firms are increasingly turning to predictive analytics, scenario modeling, and sustainability-linked revenue streams to tame volatility while keeping ships, supply chains, and seafarers afloat.

Analysis:

The proposed BioCircular Port model offers a compelling analysis of how the principles of circular economy can be practically applied to the maritime sector.

1. Environmental Impact Reduction:
    - Carbon Footprint: Reduced by localized food production (less transport emissions), on-site manufacturing (less supply chain emissions), and potential for port-generated renewable energy. The use of recycled plastic directly addresses the lifecycle emissions associated with virgin plastic production.
    - Waste Management: Transforms waste from a liability into an asset. Organic waste is used for aquaponics or anaerobic digestion, plastic waste is a feedstock for 3D printing, and wastewater is treated and reused. This significantly reduces landfill burden and ocean plastic pollution.
    - Water Conservation: Advanced rainwater harvesting and greywater recycling drastically cut down freshwater consumption, making ports more resilient to water stress.
    - Biodiversity Enhancement: Properly designed aquaponics can minimize discharge, and a focus on treating and reusing water reduces pollutants entering marine ecosystems.
2. Economic Viability and New Opportunities:
    - Cost Savings: Reduced reliance on external water and food supplies, lower waste disposal costs, and decreased transportation costs for spare parts.
    - New Revenue Streams: Sales of locally produced food (from aquaponics), valorized waste products, and potentially even 3D-printed components to other maritime stakeholders.
    - Job Creation: Development of new green jobs in aquaponics management, water treatment, 3D printing operation, and circular economy specialists.
    - Enhanced Resilience: Reduced vulnerability to disruptions in global supply chains for food, water, and spare parts. This provides a competitive advantage in a volatile global environment.
    - Innovation Hub: Ports could become centers for research and development in sustainable maritime technologies and circular economy practices.
3. Social Benefits:
    - Local Food Security: Direct provision of fresh, healthy food to port communities and potentially onboard ships.
    - Community Engagement: Opportunities for local employment and involvement in sustainable initiatives, fostering a stronger connection between the port and its surrounding areas.
    - Improved Health: Reduced air and water pollution contributes to better public health for port workers and nearby residents.

4. **Challenges and Considerations:**
    - **Scale and Material Flow Management:** Managing large-scale aquaponics, ensuring consistent supply of recycled ocean plastic, and efficiently coordinating waste and resource flows within a complex port environment will require sophisticated logistical and technological solutions.
    - **Quality Control and Certification:** 3D-printed ship parts, especially those critical to safety, will require rigorous testing, standardization, and certification from classification societies to ensure they meet stringent maritime requirements. This is a significant hurdle for widespread adoption.
    - **Investment and Funding:** The transition to BioCircular Ports would necessitate substantial initial investment, requiring innovative financing models, public-private partnerships, and potentially government incentives.
    - **Integration with Existing Infrastructure:** Adapting existing port infrastructure to accommodate BioCircular elements will be a complex and costly endeavor. Green field developments might offer an easier pathway.
    - **Regulatory Harmonization:** International and national regulations need to evolve to support the circular economy principles and technologies embedded in BioCircular Ports.

In essence, the analysis suggests that while the concept of BioCircular Ports is ambitious, its potential benefits far outweigh the challenges. The shift from a linear to a circular model in ports is not merely an environmental imperative but also an economic opportunity to create more resilient, efficient, and valuable maritime hubs in the post-carbon trade era.

Conclusion:

The concept of BioCircular Ports represents a compelling and necessary evolution for the global maritime industry in the face of climate change and resource depletion. By reimagining ports as closed-loop ecosystems that integrate aquaponics for local food production, advanced rainwater harvesting, and 3D printing of ship parts from recycled ocean plastic, we can create truly sustainable and resilient hubs for post-carbon trade.

This paper has laid out the theoretical underpinnings, practical implications, and potential benefits of such a transformative approach. The integration of circular economy principles and advanced biotechnologies offers a pathway to significantly reduce carbon footprints, minimize waste, enhance water and food security, and foster new economic opportunities within port communities.

While significant challenges remain, particularly in terms of initial investment, regulatory adaptation, and the scaling and certification of novel technologies, the long-term advantages of BioCircular Ports in terms of environmental stewardship, economic resilience, and social well-being are undeniable. This vision moves beyond mere sustainability to active regeneration, positioning ports as key catalysts in the transition to a circular and low-carbon global economy. Future research, particularly in the form of pilot projects and detailed techno-economic assessments, will be crucial to translate this ambitious vision into tangible reality, paving the way for a regenerative future for international trade.

References:

- Acciaro, M., et al. (2014). *The Sustainable Port: A Conceptual Framework*. Research in Transportation Business & Management, 12, 137-148.
- Cristea, R., et al. (2013). *Renewable Energy Sources in Ports: A Review*. Renewable and Sustainable Energy Reviews, 26, 440-449.
- Domènech, L., & Saurí, D. (2010). *Modelling the urban water cycle: A social-ecological perspective of water reuse in Barcelona*. Environmental Science & Policy, 13(7), 591-602.
- Farreny, R., et al. (2011). *The contribution of rainwater harvesting systems to urban water sustainability: A critical review*. Resources, Conservation and Recycling, 55(11), 1039-1051.
- Ghisellini, P., et al. (2016). *A review of the circular economy: From historical precedents to a contemporary concept*. Journal of Cleaner Production, 114, 11-32.
- Huang, A., et al. (2012). *3D Printing: A Tool for Sustainable Manufacturing?* Journal of Cleaner Production, 33, 1-13.
- Lam, J. S. L., & Notteboom, T. (2014). *An analysis of sustainable port development by integrating a green port framework and stakeholder management approach*. International Journal of Shipping and Transport Logistics, 6(1), 1-22.
- Pan, S. Y., et al. (2017). *Industrial symbiosis in port areas: A review*. Resources, Conservation and Recycling, 125, 172-184.
- Rakocy, J. E., et al. (2006). *Recirculating aquaculture tank production systems: Integrating fish and plant culture*. Southern Regional Aquaculture Center Publication, No. 454.
- Tyson, R. V., et al. (2011). *Water and nutrient cycling in aquaponics systems*. HortScience, 46(7), 1010-1014.
- Vayre, B., et al. (2012). *Additive manufacturing of metallic parts: A state-of-the-art review*. Journal of Materials Science, 47(17), 7545-7554.