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Terrestrial Education and Marine Structural Design: A Post-Sustainability Framework for Ocean Engineering Innovation

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ABSTRACT

This paper argues that in an era of accelerating climate change and rising sea levels, what truly matters is not merely the marine structure itself, but the foresight and adaptability embedded in its conception. As global urbanization intensifies along coastlines, and as storms grow stronger and ecosystems degrade, there is an urgent need for transformative approaches to ocean engineering and design. We introduce Terrestrial Education, an interdisciplinary framework that moves beyond conventional sustainability models by integrating ecological intelligence, regenerative systems thinking, and advanced technologies. Unlike traditional approaches that focus on minimizing harm, Terrestrial Education emphasizes active ecological restoration, socio-technical evolution, and planetary stewardship. Drawing on lessons from space exploration, such as closed-loop life support systems, autonomous environmental management, and modular habitat design, we demonstrate how these principles can inspire resilient marine infrastructures, including floating platforms, submerged laboratories, and bio-integrated offshore structures. These designs are envisioned not only for their physical durability but also for their capacity to regenerate ecosystems and foster meaningful human interaction with marine environments. The paper highlights key priorities such as adaptability to climate extremes, energy efficiency through marine renewables, and environmental integration using biomimetic materials. By aligning with the Sustainable Development Goals of the blue economy, Terrestrial Education offers a future-oriented model that harmonizes environmental, technological, and economic objectives. Ultimately, this framework provides a conceptual and operational foundation for reimagining marine structures as catalysts for innovation, educational transformation, and resilient planetary futures in the climate era.

Keywords: Terrestrial Education; Marine Structures; Floating Platforms; Blue Economy; Sustainable Development Goals (SDGs); Marine Engineering Innovation; Submerged Facilities; Underwater Habitats

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1. Introduction: Applying Terrestrial Education to Marine Structural Innovation

Humanity must adapt to a changing Earth while advancing space exploration, positioning the oceans as a key frontier for future infrastructure and innovation. Climate change and urbanization urgently require new approaches to marine habitation, especially as nearly 40% of the global population lives within 100 km of a coastline, with major cities like Jakarta, New York, and Shanghai increasingly threatened by sea-level rise, storm surges, and land subsidence [1]. In response, a new wave of marine infrastructure projects is emerging to enhance resilience and sustainability in coastal areas, reflecting a broader transition in how humanity coexists with aquatic environments.

At the same time, advancing maritime technologies are increasingly drawing from the field of space exploration, where challenges, such as autonomy, life support, and habitat design have fostered systems thinking and regenerative solutions. These developments point toward a growing convergence between two traditionally distinct domains, space and ocean engineering, which calls for a new interdisciplinary framework that surpasses the boundaries of conventional sustainability. In response to the limitations of conventional sustainability models, Terrestrial Education (TE) [2] offers a systems-based framework that repositions humanity as a regenerative force within ecosystems. Going beyond harm reduction, it promotes intelligent design, adaptive technologies, and ecologically integrated systems aligned with regenerative design and ecological engineering [3,4]. Far from being abstract, TE provides a practical foundation for embedding circularity and resilience into marine infrastructure.

This paper applies TE to the development and governance of floating cities, submerged labs, offshore energy platforms, and other complex ocean systems, revealing how educational and design strategies can foster climate resilience, sustainable blue economy development, and innovation ecosystems [5,6]. Ultimately, TE supports a shift in Sustainable Marine Structures toward a regenerative, adaptive, and systemic model, equipping professionals with both technical tools and anticipatory mindsets for stewarding marine environments.

1.1. Concrete Applications of Space-to-Marine Technology Transfer

The conceptual overlap between space and marine design is increasingly evident in engineering projects adapting space-based technologies—such as closed-loop life support, modular structures, and autonomous systems—for submerged and offshore environments. A key example is NASA's NEEMO program, which uses the Aquarius underwater habitat to test autonomy, life support, and psychological endurance in isolation. These missions have influenced both technical designs for underwater labs and educational models aligned with Terrestrial Education.

Similarly, projects like OCEANIX Busan (**Figure 1**) incorporate regenerative systems and modular designs inspired by space architecture.

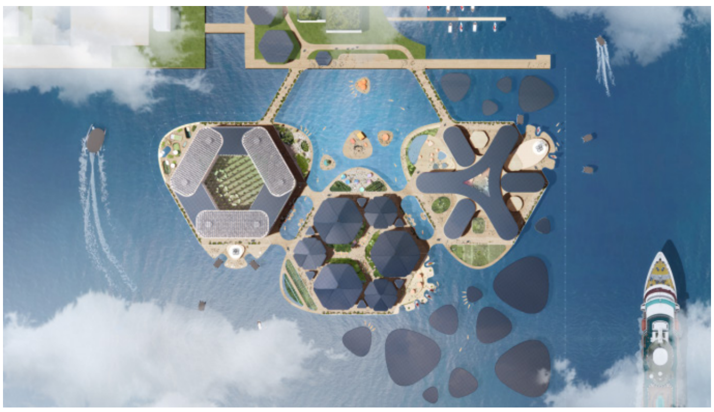

Figure 1. OCEANIX concept. Image courtesy: UN-Habitat.

1.2. Differentiating Terrestrial Education from Regenerative Design and Deep Ecology

Terrestrial Education proposes a new operational and transdisciplinary framework composed of three integrated pillars:

- **Space-Derived Operational Intelligence:** It adapts technologies and methodologies from space exploration, such as autonomous systems, closed-loop life support, and modular habitats, to develop resilient and innovative solutions for ocean-based and extreme environments. This "space-to-Earth" approach fosters adaptive thinking grounded in real-world testing.
- **Educational Transformation as a Design Driver:** Education serves as both a vehicle and a structure for developing planetary consciousness and infrastructure literacy, integrating these into curricula, vocational programs, and public engagement initiatives.
- **Transdisciplinary Capacity-Building for Complex Systems:** TE bridges disciplines including, architecture, marine engineering, AI, ethics, policy, and space science, enabling professionals to co-create regenerative infrastructures across space, marine, and urban domains using both technological and governance-based tools.

While regenerative design emphasizes built environments and eco-integrative practices, and deep ecology centers on biospheric ethics and minimal technological reliance, Terrestrial Education uniquely combines planetary ethics, space-derived technologies, and systems literacy. It positions education as a core transformative tool and promotes cross-sectoral, scalable implementation—linking infrastructure, space exploration, AI, and institutional innovation.

2. Beyond Marine Sustainability: Applying Terrestrial Education to Regenerative Marine Structures

Conventional sustainability paradigms in marine design have historically emphasized limiting environmental degradation through risk reduction and damage control [1]. Strategies such as establishing marine protected areas, reducing chemical runoff, or designing ports with minimal disruption to benthic ecosystems are foundational practices in this domain. Their primary goal is to prevent further harm rather than to restore degraded systems or enhance marine environments. While this approach is well-suited to marine protected areas, where ecosystems and the planet itself need time to recover pre-anthropogenic conditions that took millennia to develop, it remains incomplete when addressing the demands of scientific innovation or, in this context, the principles of Terrestrial Education." As noted in the United Nations 2020 report on Sustainable Development Goal 14, "*current efforts to protect key marine environments... are not yet meeting the urgent need to protect this vast, fragile resource*" [2].

The status quo is increasingly insufficient considering the current climate change impacts, including ocean acidification, deoxygenation, warming, and extreme weather events. The scale and speed of environmental change now require transformative approaches, ones that not only mitigate degradation but also contribute to long-term systemic healing.

TE, when applied to marine engineering, offers a transformative alternative to conventional sustainability approaches by promoting infrastructure that actively enhances marine ecosystems while supporting human and industrial needs [2]. Unlike models focused on minimizing harm, TE integrates technological innovation and systems thinking to empower professionals to design for regeneration and resilience. To realize this vision, TE embeds circular design principles and ethical reasoning into the training of marine engineers, planners, and policymakers [2,3]. This regenerative paradigm is increasingly reflected in applied practices. A notable example is ECOncrete [4], which uses biomimetic designs and mineral compositions to support marine life directly on infrastructure surfaces. Organisms such as oysters and barnacles enhance biodiversity and improve structural performance through a process known as natural cementation. In this model, seawalls and piers become ecological-engineered systems, providing habitat, attenuating wave energy, and stabilizing sediment [4].

The regenerative approach promoted by Terrestrial Education draws from both natural ecosystems, such as mangroves, kelp forests, and coral reefs, as well as advanced technologies. Tools such as AI, robotics, and data analytics are utilized for real-time monitoring and adaptive intervention in marine systems. For example, underwater acoustic sensors combined with machine learning can now perform reef health diagnostics and support dynamic ecosystem management [6,7]. These systems thinking parallels closed-loop life support systems developed for space missions [8]. Technologies such as air and water recycling, waste-to-energy conversion, and autonomous diagnostics, originally intended for extraterrestrial habitats, are increasingly relevant to offshore and submerged infrastructure. Terrestrial Education argues that these should be adapted to design semi-closed, self-regulating marine ecosystems. One example is the use of algal bioreactors for integrated carbon capture and oxygen production. These systems can simultaneously support waste treatment, food production, and energy generation in floating cities and ocean farms, effectively mimicking natural photosynthesis [4,9]. At its core, TE proposes a cultural and operational shift from extractive marine use to regenerative co-evolution. Infrastructure becomes an ecological actor, enabled by practices such as ocean gardening, adaptive floating architecture, and community-based fisheries, blending traditional maritime knowledge with technological innovation [3].

In summary, this transition redefines marine infrastructure as not only minimizing harm but also actively restoring and co-evolving with aquatic ecosystems.

2.1. Real-world Applications of Terrestrial Education Principles

Early implementations of TE principles, such as transdisciplinary learning, systems-based design, and space-derived methodologies, are beginning to influence marine innovation. The DEEP Sentinel habitat (**Figure 2**) exemplifies this by integrating aerospace engineering and behavioral science to simulate long-term human occupation in marine isolation, reflecting TE's model of transdisciplinary capacity-building. Similarly, OCEANIX Busan incorporates TE values by combining infrastructure, ecology, and education. Beyond its modular design (Section 1.1), the project partners with local universities and sustainability networks, turning the site into a living lab for regenerative urbanism and talent development. NASA's NEEMO program offers another concrete example, using underwater analogs to train astronauts and engineers in autonomy, resilience, and habitat maintenance. It embodies TE's immersive, systems-based pedagogy, linking environmental stressors with human and technical performance [3].

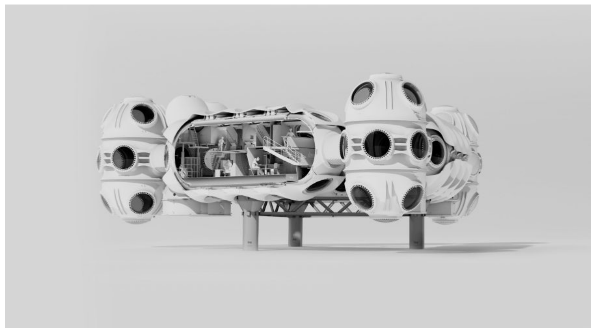

Figure 2. Concept rendering of a modular underwater habitat (@DEEP's Sentinel system), which exemplifies advanced ocean infrastructure developed through multi-sector innovation. Such projects require alliances between engineering firms, research institutions, and government agencies to address technical, human, and environmental challenges.

Additional alignment is visible in floating innovation hubs, which, although not formally labeled under TE, operate as interdisciplinary testbeds for modular infrastructure and resilient oceanic design, demonstrating TE's vision of infrastructure as both an educational and ethical interface with the planet. Recent research underscores the technical depth of this shift. For instance, Sholikhah et al. [10] assess buckling performance in stiffened panels for high-pressure environments; Nekrasov et al. [11] develop a semicircular sampling method for improved seawater/ice discrimination in altimetry; and Rusvan et al. [6] explore tidal energy potential via advanced modeling—reinforcing TE's call for site-specific, renewable, and adaptive design solutions. Together, these cases demonstrate that Terrestrial Education is not merely conceptual but offers a practical framework for advancing marine infrastructure through resilience, innovation, and cross-sector collaboration.

3. The Marine Reframing of Terrestrial Education: Building Capacity for Marine Structural Innovation

A core tenet of TE is that learning must go beyond traditional disciplines to foster planetary consciousness, a systemic awareness of Earth as an interconnected biosphere where oceans are vital to habitability, innovation, and resilience [2,9]. Education thus becomes a transformative tool for professionals and citizens to address global challenges through adaptive, integrative thinking. In the marine domain, this shift demands reimagining curricula and practices to emphasize systems-based design and technological literacy. This framework envisions futures where amphibious cities, regenerative aquaculture, and underwater labs are not just speculative but practical, scalable solutions for climate-resilient development [12,13]. Educational institutions must evolve accordingly, blending technical expertise with ecological ethics and global systems thinking to prepare learners for these emerging ocean-based realities.

Three core dimensions define the reframing of marine education through TE:

1. Ecological Intelligence and Ocean Literacy: TE centers on ecological intelligence, the ability to perceive and engage constructively with living systems—as a foundational educational goal. Within a marine context, this translates into widespread ocean literacy, as defined by UNESCO, which emphasizes understanding the ocean's role in human life and vice versa [3]. This should permeate all educational levels and disciplines. For example, students might model fish populations in math classes, explore maritime cultures in literature, or simulate international ocean policy negotiations in civics. These integrative methods develop a complex, systems-level understanding of oceans as both ecological and socio-political entities [5,6]. Such systems thinking is vital for future marine engineers and policymakers tasked with creating resilient, regenerative infrastructures.
2. Artificial Intelligence and Autonomous Marine Systems: As digital technologies reshape the marine sector, TE integrates hands-on learning in AI, robotics, and data-driven environmental monitoring. AI applications range from predicting storm surges to optimizing maritime traffic and assessing biodiversity. Tools like AUVs (autonomous underwater vehicles) support activities such as coral reef diagnostics and infrastructure monitoring [11,12]. Education should include project-based experiences, such as building sensor networks or programming current-based energy models. Programs like MATE ROV have shown how experiential learning builds both technical expertise and adaptive problem-solving [13], underscoring the need to embed such approaches into broader marine education.
3. Design Thinking for Floating and Submerged Habitats: To address the complexity of ocean-based habitation, T.E. emphasizes design thinking and transdisciplinary project work. Students might design offshore research hubs, floating cities, or regenerative aquaculture platforms, drawing knowledge from architecture, engineering, biology, and governance. For instance, designing a floating city for 10,000 people would require balancing energy, food, waste, water, and climate resilience, all within ecological and structural constraints [11,14]. Such simulated projects cultivate iterative innovation and ecological accountability in future professionals.

3.1. Proposed Learning Modules for Marine-Oriented Terrestrial Education

To implement the vision of TE in practice, the authors propose a modular curriculum for integration into university, vocational, and professional training programs. These modules aim to foster interdisciplinary competence in ocean systems, build ecological literacy, and cultivate the technical and ethical proficiency needed for the emerging Blue Economy. Core thematic modules:

- **Ocean Systems Engineering**: Study of marine biogeochemical cycles (e.g., carbon, nitrogen, and phosphorus) and their relevance to closed-loop life support in submerged and floating habitats.
- **Blue Technology and Bio-Integrative Engineering**: Exploration of offshore renewable energy (wind, wave, and tidal), biomimetic materials, and regenerative marine construction, emphasizing resilience and ecological integration [9,10,15].
- **Climate Adaptation Design Studios**: Practice-based labs focused on amphibious architecture, coastal defense systems, and climate-responsive infrastructure design.
- **Marine Robotics and Environmental AI**:Technical training in autonomous marine vehicles, sensor systems, and AI applications for environmental monitoring.
- **Ocean Governance and Ethics**: Engagement with legal and ethical frameworks, including marine spatial planning, high seas treaties, and responsible use of marine AI and natural resources [16,17].
- **Applied Internship in the Marine Domain**: Field-based learning through partnerships with initiatives like OCEANIX, DEEP, and Proteus, giving students hands-on experience in floating infrastructure and underwater labs [18,19].

This marine-focused TE curriculum is designed to cultivate a new generation of professionals, engineers, designers, policymakers, and entrepreneurs who are fluent in both ecological systems and advanced marine technologies, such as floating cities, autonomous offshore platforms, and submerged research habitats. As oceans become increasingly critical for climate adaptation, food security, and energy, this educational model prepares students to lead sustainable and regenerative development in marine environments.

3.2.Toward a Standardized Curriculum for Terrestrial Education

To facilitate adoption across diverse institutions, the authors propose an educational standard that supports both foundational learning and focused curricula, thereby enhancing the overall learning experience. This curriculum structure reflects the core values TE aims to propose, emphasizing systems thinking, ecological integration, and planetary ethics. As part of this effort, the authors are actively developing collaborations with academic institutions to co-develop and pilot components of this draft program. These partnerships will inform context-specific revisions and help move the framework from conceptual design to applied curriculum.

Suggested Program Formats:

- TE-aligned professional certifications in marine systems thinking.
- Interdisciplinary summer schools combining oceanography, ethics, and digital tools.
- Laboratory activities are co-hosted by universities and innovation clusters.
- Field internships with Blue Economy startups and ocean observatories.
- Virtual courses in collaboration with space agencies and underwater analog labs (e.g., NEEMO).

Examples of Course Topics:

- Introduction to terrestrial education: principles and scope.
- Systems rethinking for marine infrastructure: feedback, loops, and life-cycle modeling.
- Space-to-marine technology transfer: analog missions and dual-use innovation.
- Bio-regenerative engineering: living systems, closed-loop design, material circularity.
- AI and robotics in marine contexts: blue robotics and environmental AI.
- Ethics and governance of the ocean commons: rights of nature, equitable access.
- Designing for climate resilience: floating cities, modular adaptability.
- Communication in marine innovation: language, narratives, anti-greenwashing.
- Mission planning and simulation: applying space analogs to marine education.

4. Reinterpreting the UN SDGs for Marine Structures through Terrestrial Education

The United Nations Sustainable Development Goals (SDGs) provide a global framework to address urgent challenges across social, environmental, and economic domains. However, the practical application of these goals, particularly in marine infrastructure, requires reinterpretation. Traditional sustainability approaches, focused mainly on harm reduction, are no longer sufficient given the escalating planetary crises, especially in marine contexts where ocean health, climate resilience, and Blue Economy development converge [5,6]. Emerging infrastructures, such as floating cities, submerged habitats, and eco-integrated offshore systems, hold the potential to support SDG implementation. However, realizing this potential depends on the emergence of educational models that equip professionals with interdisciplinary and systems-based expertise. In this context, TE offers a transformative framework that connects high-level global policy goals to practical, local innovations in marine development. It emphasizes not only sustainability, but also systemic regeneration, social equity, and long-term resilience. To make this link explicit, the authors propose **Table 1** that maps key SDGs to marine infrastructure goals and educational strategies. Each goal is reframed through the lens of TE, offering clear pathways for training professionals who can design regenerative, ocean-based futures.

Table 1. Reinterpreting the SDGs for Marine Structures through Terrestrial Education.

SDG	Marine Context	Role of Terrestrial Education
SDG 1 – No Poverty	Marine industries can create livelihoods through aquaculture, offshore energy, and floating infrastructure.	Train coastal populations in blue economy skills (e.g., offshore maintenance, and robotic aquaculture).
SDG 2 – Zero Hunger	Sustainable ocean farming can enhance food security with minimal land use.	Educate on ocean farming techniques and integrate sustainable aquaculture practices.
SDG 3 – Good Health and Well-being	Floating clinics and clean marine infrastructure improve public health outcomes.	Train professionals in marine healthcare delivery and bio-health monitoring systems.
SDG 4 – Quality Education	Floating schools and remote education systems improve accessibility.	Promote marine-focused STEM programs and virtual learning linked to marine environments.
SDG 5 – Gender Equality	Expanding access to marine industries empowers women in technical and leadership roles.	Support inclusive STEM education and leadership training in ocean technologies.
SDG 6 – Clean Water and Sanitation	Marine structures require closed-loop water treatment and pollution control systems.	Teach marine water engineering, waste recycling, and sustainable sanitation design.
SDG 7 – Affordable and Clean Energy	Oceans provide renewable energy from wind, wave, and tidal resources.	Train technicians and engineers in offshore renewable energy systems [13,20].
SDG 8 – Decent Work and Economic Growth	Marine industries offer diverse employment in engineering, research, and renewable energy.	Develop vocational programs in marine technology and sustainable entrepreneurship [8].
SDG 9 – Industry, Innovation and Infrastructure	Resilient, modular offshore infrastructure requires continuous innovation.	Support interdisciplinary R&D training and marine innovation incubators [3,4].
SDG 10 – Reduced Inequalities	Equitable development of marine structures can benefit vulnerable coastal communities.	Promote inclusive marine development education and participatory governance training.
SDG 11 – Sustainable Cities and Communities	Floating and offshore infrastructure contribute to urban climate resilience.	Educate planners in marine urban design ('aquatecture') and community engagement [13,15].
SDG 12 – Responsible Consumption and Production	Marine structures demand circular economy principles and resource efficiency.	Teach sustainable material sourcing, lifecycle design, and resource recovery methods [10,11].
SDG 13 – Climate Action	Marine infrastructures can mitigate climate risks and support adaptation.	Train specialists in ocean-based climate resilience strategies and carbon sequestration methods [18].
SDG 14 – Life Below Water	Marine structures can actively support marine biodiversity and ecosystem health.	Educate on eco-engineering techniques and citizen science in marine conservation [10,11].
SDG 15 – Life on Land	By expanding sustainable use of ocean spaces, pressure on terrestrial ecosystems is reduced.	Teach integrated coastal and marine resource management.
SDG 16 – Peace, Justice, and Strong Institutions	New governance frameworks are required for international marine developments.	Train maritime policy experts and develop curricula on ethical marine governance [21].
SDG 17 – Partnerships for the Goals	Cross-sector collaboration is essential for sustainable marine infrastructure.	Foster university-industry-NGO alliances and develop international marine education networks.

These reinterpretations show that marine infrastructure is both compatible with the SDGs and instrumental to achieving them. For example, the development of floating cities can simultaneously address SDG 11 (Sustainable Cities), SDG 13 (Climate Action), and SDG 14 (Life Below Water) when designed using biomimetic materials, powered by marine renewables, and governed through inclusive, participatory processes [5,18,19]. Furthermore, these SDG-aligned educational pathways reinforce the notion that regeneration and innovation must go hand in hand. For instance, training students in the use of AI for marine monitoring can contribute to improved conservation (SDG 14), but also to the generation of new employment opportunities (SDG 8), enhancement of public health (SDG 3), and supporting responsible innovation (SDG 9) [3].

4.1. Integrating Traditional Ecological Knowledge

A core tenet of TE is the recognition that planetary literacy cannot be fully realized without the meaningful integration of Indigenous and local knowledge systems, particularly in marine environments where cultural and ecological relationships are profoundly interconnected. Within this framework, Traditional Ecological Knowledge (TEK), the cumulative body of observations, practices, and philosophies developed by Indigenous and coastal communities, offers both historical continuity and practical strategies for resilience, sustainability, and ecosystem stewardship.

TE incorporates TEK not as a peripheral supplement but as a co-equal epistemology alongside scientific and technological approaches. This integration is evident in both its curricular design and infrastructural methodologies. For example, the navigational systems of Pacific Islander cultures, which rely on star paths, ocean swells, and ecological indicators, are employed in marine education programs aligned with TE to teach non-instrumental navigation and foster deep, place-based ecological literacy. Similarly, the Hawaiian ethic of Malama Honua, "to care for the Earth", is embedded into governance and planning modules, emphasizing ethical stewardship and intergenerational accountability in the design of marine infrastructure. Rather than appropriating Indigenous knowledge as isolated content, TE supports collaborative design processes that foreground community participation and cultural relevance. This includes developing curricula that interweave satellite-based sensing with oral traditions and communal memory, as well as planning marine infrastructure that respects biocultural landmarks and seasonal cycles. In doing so, Terrestrial Education not only expands the intellectual and ethical scope of marine systems thinking but also establishes a more just and ecologically grounded foundation for the co-creation of resilient ocean-based futures.

5. Industrial Alliances and Oceanic Innovation Ecosystems

The grand challenge of establishing a resilient civilization at sea encompasses ecological, technological, economic, and geopolitical complexities so extensive that no single actor—whether a company, academic institution, or government—can address them in isolation. The scale and systemic nature of ocean innovation demands cross-sectoral collaboration, giving rise to a new generation of industrial alliances that fuse expertise across architecture, marine engineering, energy systems, digital technologies, and ecological science. These alliances are increasingly recognized as essential engines of marine innovation ecosystems, enabling shared risk-taking, accelerated R&D, and scalable deployment of infrastructure for ocean-based habitation and industry [9]. A central example of this collaborative model is the OCEANIX Busan consortium [14,22], which unites UN-Habitat, the municipal government of Busan, and global design and engineering firms, including BIG, Arup, SAMOO, and the MIT Center for Ocean Engineering. This coalition exemplifies how transdisciplinary partnerships can co-develop modular floating infrastructure that is both ecologically, socially and technically resilient. It functions as both a technological testbed and a governance model for cross-sectoral ocean innovation ecosystems. Supporting this coalition are technology providers like Wärtsilä, a leader in marine propulsion and energy systems, and The Global Coral

Reef Alliance, which focuses on habitat regeneration and ecosystem services. Together, they reflect the interdisciplinary structure required to develop the complex social-ecological systems of future marine cities. The OCEANIX model itself can be seen not only as a prototype for sustainable offshore infrastructure but also as a living laboratory for integrated development practices that exemplify systems thinking and regenerative principles central to TE [2,3,13].

These alliances cannot rely solely on technical solutions. They require educational and strategic frameworks that anticipate the complexity and ethics of building permanent infrastructure in dynamic, sensitive, and often legally ambiguous marine environments. This is where Terrestrial Education functions as a dual catalyst, both as a builder of future human capital and as a strategic influence on how industries evolve and align with ecological imperatives. At the same time, this paper recognizes a central risk in many future-oriented frameworks: advanced technologies and appealing language, such as "blue growth" or "resilience", might be used to repackage extractive practices in a more acceptable form. Terrestrial Education responds to this risk through specific, feasible mechanisms by encouraging marine infrastructure projects to involve local communities, ecological researchers, and civil society stakeholders from the earliest planning phases, not as a formality but as a structural requirement. Tools such as collaborative design workshops, open review boards, and full-life-cycle assessments are incorporated into the development process to evaluate not only technical feasibility but also the long-term ecological and social impacts.

Through its curricula and strategic planning tools, TE cultivates a mindset of responsible skepticism toward technological solutions by prompting practitioners to ask: Who benefits from this infrastructure? What long-term effects are being externalized? Can this system be adapted or dismantled in the future without harm? These questions are embedded in both design decisions and educational models, helping ensure that innovation remains accountable to the ecosystems and communities it affects. This includes resisting the temptation to use terms like "regenerative," "blue," or "sustainable" as unchecked marketing tools. Instead, TE proposes the development of ethical design audits, community co-governance, and life-cycle impact frameworks to ensure that ocean innovation ecosystems do not merely reproduce the same extractive logic they intend to replace. The incorporation of planetary boundaries, indigenous knowledge systems, and rights-of-nature perspectives into design processes is not optional, but a core dimension of the TE approach.

From an educational standpoint, TE proposes educational pathways essential for preparing engineers, designers, data scientists, and project managers capable of contributing meaningfully to marine innovation alliances. For example, the collaboration between Ultra Safe Nuclear Corporation (USNC) and Peregrine Turbine Technologies illustrates how dual-use technologies, originally developed for space habitats, are being adapted to remote marine environments [14]. These modular, compact, and autonomous energy systems are designed to be decentralized, low-maintenance, and self-regulating, aligning with the energy autonomy requirements of both deep-sea infrastructure and space colonization.

This convergence is particularly visible in the emergence of oceanic innovation hubs and Blue Economy clusters. In Norway, for instance, ocean tech clusters bring together robotics companies, offshore energy firms, and research centers under a unified innovation ecosystem. Singapore's maritime innovation zone similarly fosters R&D across smart ports, maritime AI, and ocean engineering. These regional ecosystems incubate experimental infrastructure and emerging startups but also restructure their programming around regenerative and adaptive goals that resonate with the values of TE [5,6]. Within these ecosystems, floating modular systems, bioregenerative structures, and circular economy models are becoming the new normal, replacing traditional linear models of extraction and disposal. Companies developing marine platforms are increasingly favoring materials that promote biodiversity, energy systems that integrate tidal and solar input, and architectural forms designed for hydrodynamic efficiency and ecological integration [5,10,11]. These choices are not only environmentally beneficial, but they are also becoming commercially viable and socially necessary due to tightening environmental regulations and rising climate risks.

Ultimately, Terrestrial Education helps steer industrial alliances away from short-term competitiveness and toward long-term planetary alignment. TE ensures that the infrastructures developed over the next decades will not simply be resistant to collapse, but resilient and contributive, enhancing ecological systems, enabling inclusive economies, and catalyzing sustainable governance of the marine domain. More than a training framework, Terrestrial Education actively shapes the emerging culture of the marine industry itself. At the same time, it holds the transformative capacity to activate entirely new pathways of industrial development and economic growth, particularly in sectors aligned with the Blue Economy and ocean-based resilience innovation. This vision of future-ready marine industry ecosystems reflects a broader paradigm shift from engineering against nature to engineering with nature and from siloed innovation to co-created, planetary-scale design.

Translating space-based technologies into marine infrastructure does indeed pose substantial logistical and financial challenges. However, TE addresses these barriers directly by emphasizing scalable design, cost-adaptive modularity, and dual-use innovation ecosystems. A central strategy involves leveraging technologies originally developed for space missions, such as autonomous systems, compact life-support modules, and closed-loop energy or water recycling units, that are now being adapted for Earth-based applications. These solutions benefit from cross-sector R&D investments, which reduce individual project costs through shared innovation pipelines and enhance the reusability of design platforms.

TE also promotes modular, containerized architectures (inspired by space analogs), which allow marine infrastructure to be deployed incrementally, scaled flexibly, and transported efficiently. This not only reduces up-front capital requirements but also enhances logistical adaptability in island, coastal, and deep-sea settings. This translation of space-based technologies into scalable marine infrastructure is not just a means of cost optimization. Still, it also triggers a powerful reverse technology transfer, catalyzing new funding streams, entrepreneurial ventures, and industrial applications. As space technologies are adapted to marine conditions, they generate spin-offs in robotics, AI, bio-regenerative systems, and remote operations, creating economic multipliers that extend far beyond the original infrastructure.

Finally, TE supports financial feasibility through policy and educational pathways: training a new workforce to operate and adapt space-derived systems locally while advocating for planetary infrastructure policies that include marine innovation in space-sector funding schemes. In this way, TE helps bridge the economic and operational divide, turning high-cost inspiration into scalable, opportunity-rich deployment.

6. Preventing Greenwashing in Blue Growth Initiatives

As blue growth emerges as a dominant narrative in marine infrastructure and policy, the risk of greenwashing—namely, the strategic deployment of sustainability rhetoric without demonstrable ecological integrity—has significantly increased. The TE framework addresses this challenge through a combination of technical safeguards and educational interventions. On the technical front, TE supports the integration of independent verification mechanisms such as ISO environmental standards [23,24], Environmental Product Declarations (EPDs) [25], and ESG impact audits. These instruments provide standardized, policy-aligned methodologies for assessing the environmental performance of marine infrastructure across complex life-cycle scenarios involving energy systems, material flows, and ecosystem interactions. Equally important is the educational dimension of TE, which promotes ecological literacy and critical sustainability analysis across stakeholder groups. By embedding environmental assessment into engineering curricula, vocational training programs, and public education initiatives, TE cultivates a new generation of professionals and citizens equipped to evaluate sustainability claims and enforce institutional accountability critically.

Additionally, TE advocates for open-access performance dashboards and community-driven monitoring systems that provide real-time transparency on metrics such as energy consumption, biodiversity impact, and material reuse. These platforms democratize environmental data and support multi-level governance, bridging the gap between sustainability discourse and measurable outcomes. Thus, Terrestrial Education functions not only as a conceptual and operational framework but also as an ethical filter and accountability mechanism. It ensures that blue growth initiatives are aligned with verifiable planetary value rather than serving as vehicles for performative compliance.

7. Language Evolution and the Culture of Marine Transformation

With human activity expanding into marine environments, the evolution of language and cultural narratives becomes crucial in framing, legitimizing, and guiding this transformation. Like past transitions, from the industrial revolution to the space age, marine adaptation requires the invention of new terms, metaphors, and conceptual frameworks that shape public discourse, policy, and investment [2,17]. Terminologies such as *Blue Economy*, *Hope Spots*, and *Blue Stewardship* exemplify how language can reframe the ocean from a site of crisis or extraction to one of regeneration and innovation, encouraging constructive engagement among communities and policymakers [6,16].

This discursive shift is further deepened by concepts such as Ocean Rights and Marine Ecosystem Personhood, which echo legal movements that recognize natural entities, like rivers and forests—as rights-bearing subjects. These frameworks challenge anthropocentric legal systems and introduce relational, systems-based ethics that aligns with the principles of TE [15]. Complementary indigenous philosophies, such as the Polynesian *Malama Honua* ("to care for Island Earth"), offer culturally grounded models of reciprocity and balance that can meaningfully inform global marine discourse.

TE emphasizes the importance of semantic accountability and narrative responsibility in shaping marine futures. Mass media, speculative design, and public storytelling play powerful roles in normalizing radical innovations—such as ocean farms, floating cities, and amphibious housing, by rendering them culturally legible and emotionally resonant [19,24].

To address this, TE embeds ethical storytelling, science communication, and critical media literacy into professional training. Future marine engineers, designers, and policymakers must be equipped not only with technical expertise but also with the narrative tools to articulate inclusive, transparent, and regenerative visions. In doing so, language becomes a catalyst for cultural transformation.

7.1. Vocabulary Innovation and the Rise of Marine Disciplines

The use of emerging terms such as "Aquatecture" and "Blue Robotics" reflects a shifting paradigm in how we conceptualize marine space, infrastructure, and agency [4,19]. These disciplines formalize what was once fringe experimentation, transforming it into institutional knowledge domains and thereby reinforcing the legitimacy and professionalization of marine transformation work.

- ***Aquatecture*** refers to architectural practices intentionally designed for aquatic or semi-submerged environments, emphasizing ecological integration and resilience [26]. It overlaps with traditional marine architecture by addressing hydro-symbiotic structures that support cohabitation with marine ecosystems.
- ***Blue Robotics*** shifts the emphasis from industrial or military functions to autonomous, regenerative, and cooperative systems designed for ecological monitoring, marine construction, and long-term cohabitation. Unlike conventional Remotely Operated Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs), Blue Robotics aligns with Terrestrial Education by prioritizing environmental ethics and transdisciplinary coordination.

Moreover, new roles are being defined within the public and private sectors to manage this transformation. Job titles like "Director of Ocean Innovation Strategy" signal the growing specialization and recognition of leadership required to oversee complex oceanic systems.

In international diplomacy and policy forums, phrases like "shared ocean heritage" and initiatives like "One Ocean, One Future" encapsulate a shift toward solidarity and global responsibility. These slogans help rally support across geopolitical boundaries, reframing the ocean as a common responsibility of all nations rather than a resource to be competed over. To ensure that such phrases are not merely symbolic, Terrestrial Education proposes practical mechanisms to operationalize "shared ocean heritage" through both legal frameworks and educational strategies. These include aligning with the United Nations Convention on the Law of the Sea (UNCLOS) and the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement, which provide legal foundations for ocean commons and equitable access to marine genetic resources [27]. In practice, this means supporting community-based marine spatial planning, promoting legal and policy literacy in marine education curricula, and embedding participatory co-governance into innovation ecosystems. Educational institutions play a key role by incorporating modules on marine rights, ethical governance, and civic ocean stewardship, ensuring the phrase "shared heritage" translates into enforceable norms and inclusive protocols, rather than just inspirational language.

This approach prevents abstraction by anchoring symbolic concepts in accountable structures, planetary ethics, and localized decision-making processes, all of which are central to the Terrestrial Education framework.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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