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Algae City: AI-Generated Urban Identity and the Computational Reconfiguration of Coastal Waste

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ABSTRACT: This study presents Algae City of Qingdao, an AI-driven urban framework that transforms Ulva algae from waste into a regenerative material intelligence system. Unlike Qingdao's linear disposal model, which disregards algae's bio-computational potential, this research leverages generative AI to integrate algae into bio-digital infrastructures, adaptive urban morphologies, and participatory design interfaces. Moving beyond industrial repurposing or cultural reframing, Algae City functions as a self-evolving urban identity, continuously recalibrated through environmental and social interactions. By embedding AI as an active agent in branding and spatial formation, this study redefines waste, material agency, and urban metabolism, positioning computation as the catalyst for a new synthetic ecology in intelligent city design.

KEYWORDS: Algae City; Algae Blooming; AI Urbanism; Circular design; Generative Design

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1. Introduction

1.1. Rethinking Waste as Resource

In contemporary ecological discourse, waste is often seen as an endpoint—a surplus material to be discarded or remediated. This linear perception neglects waste's latent potential within circular systems of production and transformation (McDonough & Braungart, 2002). The recurring Ulva algae blooms in Qingdao exemplify this tension: while these outbreaks—triggered by nutrient pollution and oceanic current shifts (Zhang et al., 2019)—are framed as an environmental crisis, they also constitute an abundant, renewable bio-resource capable of redefining coastal materiality.

Qingdao has witnessed recurrent Ulva algae (Ulva prolifera) blooms since 2007, exacerbated by intensified laver aquaculture in Jiangsu Province. The algae detach from aquaculture rafts and drift northward, accumulating along Qingdao's coastline. According to recent reports, more than 100,000 tons of Ulva algae are removed from Qingdao's shores annually during peak bloom seasons (Ye et al., 2011). These large-scale removal operations involve hundreds of fishing vessels and disposal teams, yet the prevailing strategies—incineration, landfill, or offshore dumping—merely externalize the issue without integrating algae into a sustainable material cycle (Madejón et al., 2022).

Figure 1. Removing Ulva algae at a coast in Qingdao, China, Photo by Author

The Chinese proverb "眼不见，心不烦" ("what the eye doesn't see, the heart doesn't grieve") aptly characterizes this approach. Rather than addressing the root causes or potential value of Ulva algae, management efforts prioritize rapid removal and concealment. This not only externalizes the issue but also reinforces the perception of algae as an intrusive and unwanted material.

This study advocates for an alternative vision—one that redefines Ulva algae not as a pollutant to be removed, but as a material resource to be designed with, celebrated, and integrated into urban and ecological systems. By leveraging AI-driven design protocols and bio-computational synthesis, this research proposes a paradigm shift, transforming Ulva algae from an environmental nuisance into an adaptive urban material system. Through AI-enhanced material transformation, Ulva algae can be reconfigured into regenerative biopolymers, adaptive urban structures, and localized material economies. This transformation is not merely functional—optimizing material cycles—but also aesthetic, reframing public perception of waste and positioning it as a generative force in urban design.

By embedding bio-digital manufacturing, generative material computation, and adaptive urban infrastructures within an AI framework, Algae City emerges as both a speculative and actionable vision. Here, Ulva algae is no longer a substance to be eliminated, but an active agent shaping synthetic coastal landscapes, material innovation, and participatory design processes. This research ultimately demonstrates how waste can be reprogrammed into a resource, forming the foundation of a circular design system that seamlessly integrates ecology, technology, and cultural identity.

1.2. Research Problem and Objectives

Qingdao's current management of Ulva algae follows a linear economic model, where the material is removed and discarded rather than reintegrated into sustainable cycles. This approach reduces waste to a problem to be eliminated, overlooking its potential as a dynamic, designable resource. Drawing on Cradle to Cradle principles (McDonough & Braungart, 2002) and expanding the concept of computational material circularity outlined in Biodesign in the Age of Artificial Intelligence: Deep Green (Pasquero & Poletto, 2023), this study challenges conventional waste narratives and proposes a regenerative paradigm. Through Generative AI-driven bio-computation, it envisions a methodology where Ulva algae is not merely repurposed but structurally embedded into an adaptive synthetic ecology—a self-evolving system that responds to environmental flux and urban metabolic processes.

The selection of AI methodologies—specifically, generative adversarial networks (GANs) for form generation, reinforcement learning for material optimization, and neural network predictors for environmental responsiveness—was based on their proven capability to synthesize complex material behaviors and adapt dynamically to fluctuating environmental datasets. The evaluation criteria prioritized scalability, ecological adaptability, and computational efficiency to ensure effective integration into urban metabolisms.

This study investigates how AI-driven design methodologies can redefine waste perception through circular design principles, transforming Ulva algae into both a meaningful material economy and a new urban aesthetic paradigm. Rather than treating algae as an unwanted externality, this research integrates it into generative urban systems, computational design strategies, and participatory biofabrication. By developing an AI-driven computational framework, the study explores how algae can be processed and re-synthesized into architecturally viable forms, redefining synthetic materiality through bio-digital workflows that challenge conventional notions of waste. Additionally, it examines AI-enhanced participatory models, enabling citizen engagement in algae-based urban interventions beyond top-down waste management strategies. Ultimately, this research positions Algae City as a speculative yet functional branding model, shifting algae from an environmental liability to a designed ecological identity embedded within Qingdao's urban fabric.

1.3. Conceptual Framework: Waste as Innovation

The transformation of waste into value is a defining force in urban and material culture. Throughout history, cities have integrated waste economies into their industrial infrastructures, reshaping discarded materials into economic and cultural assets. E-Waste City and Graffiti City exemplify how pollutants once seen as urban blights evolved into defining elements of city identity. Algae City follows a similar trajectory, but unlike previous transformations, its evolution is computationally emergent rather than manually curated.

What sets Algae City apart is its reliance on AI not as a tool of optimization, but as an active computational agent. E-Waste City emerged through industrial integration, repurposing discarded electronics as secondary resources within global recycling economies. Graffiti City followed a different path, transforming through visual revaluation, where informal street art evolved into a curated cultural commodity. Algae City introduces an alternative model—one neither market-driven nor socially adopted, but continuously recalibrated through AI-generated material flows, environmental interactions, and public engagement.

This transformation begins with algae being treated as an environmental nuisance, sparking localized material experimentation. Researchers, institutions, and designers explore its biodegradable potential, leading to early applications in construction and product design. AI-driven computational workflows scale these efforts, elevating algae from a raw material to an integral component of urban metabolism. Public-facing AI interfaces enable citizen participation, shifting perceptions from waste management to design agencies. As AI computation integrates algae-based structures into the evolving cityscape, its role expands beyond experimental prototypes into infrastructural and economic systems.

Algae City's transformation unfolds in three distinct phases (Figure. 2): the initial stage of waste perception and localized material research, the intermediate stage of computational integration and morphogenetic branding, and the final stage of large-scale adoption within urban policies and infrastructures. Unlike traditional branding, which is imposed through symbolic representation, AI computation generates urban identity as an emergent and continuously evolving phenomenon.

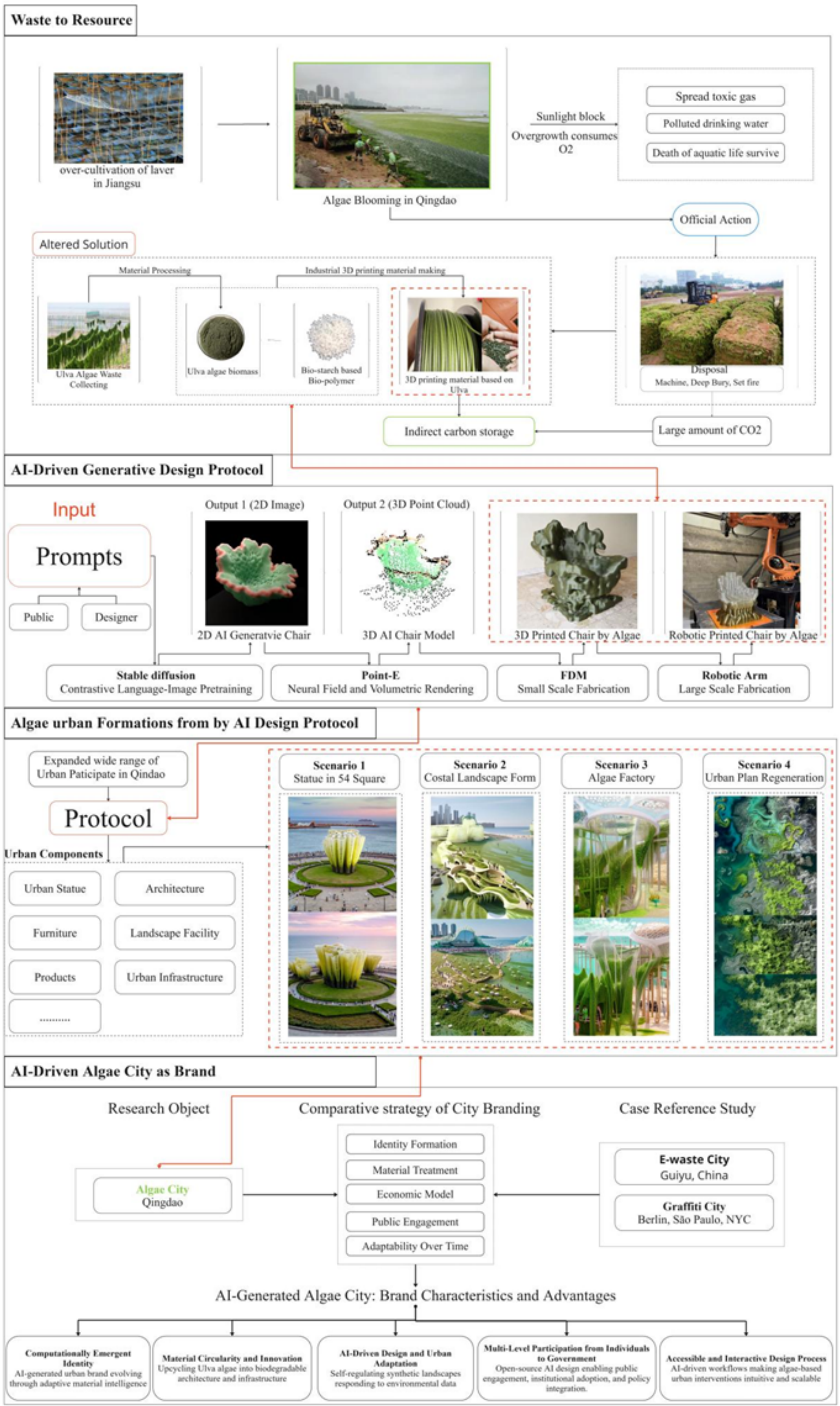

Figure 2. AI-Driven Algae City Model: A Computational Framework for Urban Branding and Circular Materiality

This process departs from traditional branding, where identity is imposed through symbolic representation. Instead, Algae City computationally generates its urban brand, with AI acting as both mediator and catalyst. Branding is neither static nor curated but emerges dynamically from the interplay of material intelligence, environmental adaptation, and participatory design. AI does not merely optimize waste; it actively constructs identity, positioning algae as an evolving force within Qingdao's synthetic coastal landscape. The next chapter examines how computational design translates algae's material intelligence into urban identity, redefining waste not as a repurposed byproduct but as a reprogrammed agent of spatial and economic transformation.

2. Computational Design Framework—Synthesizing Algae Waste into Architectural Systems

2.1. Precedents of Algae-Based Design: From Experimental Prototypes to Public Recognition

The intersection of materiality, ecology, and computation has long been a site of architectural experimentation. Throughout history, emergent materials often face initial rejection before achieving cultural assimilation. Over time, they shift from the periphery of architectural practice to the mainstream of urban discourse. Algae-based design follows a similar trajectory, evolving from an ecological anomaly into an agent of urban identity. To ground Algae City's speculative premise in historical and contemporary architectural discourse, this section examines experimental precedents in which non-conventional materials – including algae – have been used as both functional and symbolic elements in design.

Over the past decade, algae has become a focal point in architectural and industrial research, particularly within bio-design and sustainability discourses. No longer regarded merely as an ecological byproduct, algae-based materials have been repositioned as viable alternatives to conventional resources, driven by advancements in bio-fabrication and computational design. This shift aligns with broader efforts to integrate regenerative material cycles into architectural practice, challenging traditional boundaries between waste and resource.

A significant demonstration of this potential was the author's algae-based material research, exemplified by the Algal-table 2.0 prototype presented at a WWF exhibition in 2023 (Figure 3). This public installation drew substantial engagement. The prototypes on display were not merely experimental artifacts but critical provocations, positioning algae as an aesthetic and structural material capable of redefining sustainable design practices. To support these inquiries, the Algal-table 2.0 was fabricated using a composite material composed of approximately 50% Ulva algae powder, 30% bio-based resin, and 20% cellulose fibers. A hybrid fabrication process combining 3D printing and hot-pressing techniques was employed to enhance structural performance, achieving a tensile strength of approximately 12 MPa and demonstrating high resistance to moisture exposure. By integrating bio-derived materials into domestic and architectural applications, these projects underscored algae's scalability within the built environment. Beyond their role as technical demonstrations, they served as speculative inquiries into the role of computational fabrication in transitioning experimental biomaterials into deployable urban solutions. This work reinforced algae's potential not just as a sustainable alternative, but as a catalyst for rethinking material circularity in design and construction.

Figure 3. Algal-table 2.0 in WWF Exhibition,Natural History Museum of China, Beijing, Photo by Author

Historical shifts in material acceptance reveal a recurring pattern: materials are initially dismissed as waste or anomalies before becoming embedded in industry and architecture. Steel, for example, was once an exotic and costly material before it became synonymous with modern architecture in the early 20th century. Similarly, early experiments with engineered wood and mycelium were confined to experimental bio-design studios but have since entered mainstream architectural applications. Algae, currently at the fringes of material innovation, appears to follow this evolutionary trajectory — with the key difference that its adoption is being driven not just by industrial scaling, but by computational design protocols and digital fabrication.

Translating biological waste into computationally augmented material requires creative synthesis, computational adaptation, and collaborative fabrication, rather than traditional performance-based optimization. Instead of prioritizing conventional efficiency metrics, this AI-driven approach emphasizes reinterpretation, upcycling, and novel aesthetic possibilities. The robotic fabrication of early prototypes demonstrates algae's expressive and constructive potential, forging new intersections between ecological cycles and architectural fabrication (Figure. 4).

Figure 4. Robtic Fabrication Process of Algal-table 2.0, Photo by Author

While these bio-design experiments demonstrated the potential of algae-based materials, they were inherently constrained by manual fabrication techniques, which limited scalability, complexity, and adaptability. The transition to AI-driven workflows addresses these bottlenecks: AI algorithms can autonomously generate, adapt, and optimize algae-derived morphologies across multiple scales, enabling dynamic material responses to environmental conditions and significantly expanding the architectural possibilities beyond what manual crafting can achieve.

By integrating algae into a parametric design framework, these precedents lay the foundation for Algae City's core methodology, combining AI-driven form generation, robotic fabrication, and adaptive material intelligence. Unlike many biomaterials that require extensive post-processing, algae's inherent properties suit additive manufacturing – enabling direct material deposition for large-scale architectural applications.

Although these precedents prove the viability of algae-based design, they were constrained by traditional design workflows relying on predefined models and manual iteration. An AI-driven paradigm marks a critical departure from these limitations, reframing material experimentation as an autonomous, self-optimizing process. AI not only increases efficiency; it fundamentally alters the design methodology, enabling scalable, adaptive, and participatory frameworks beyond the scope of any individual designer.

At the urban scale, Algae City transcends isolated experimental applications, evolving into a systemic ecological strategy. AI-driven workflows enable real-time adaptation of algae-based formations to changing environmental parameters such as coastal erosion, hydrodynamic forces, and atmospheric conditions (Menges, 2012). This dynamic recalibration yields generative spatial formations previously inaccessible through conventional design methods (Pasquero & Poletto, 2016). More significantly, AI-mediated design participation expands accessibility, transforming algae-based urbanism from a niche research inquiry into a publicly engaged ecological infrastructure. By integrating generative platforms that allow local communities, designers, and policymakers to contribute, AI democratizes the design process, shifting Algae City from a closed architectural discourse into an adaptive, co-evolutionary network (Schumacher, 2020; Batty, 2018).

This shift lays the foundation for Section 2.2, where AI-driven protocols further redefine algae's architectural role, enabling the emergence of synthetic morphologies that evolve in real time. The precedents discussed here not only provide conceptual references for bio-computational material systems but also demonstrate how AI transforms algae from a passive ecological by-product into an active agent in urban morphology.

2.2. AI as a Generative Medium: From Algae-Based Material to Synthetic Morphologies

The integration of AI into design workflows has redefined authorship and participation in computational design. Unlike traditional parametric methods that demand specialized scripting expertise, AI-driven automation enables a more intuitive, accessible model of generative design. This shift moves computational processes from expert-driven workflows to open-ended frameworks, allowing non-specialists to engage with AI-generated solutions. The Ulva Chair – Urban Furniture experiment exemplifies this transformation, demonstrating how AI replaces manual scripting with an interactive, self-adjusting design protocol.

Rather than operating as a static design artifact, the AI workflow behind the Ulva Chair establishes a continuous feedback loop between user input, material properties, and generative computation. AI does not merely optimize formal geometry but facilitates real-time iteration, where design intent is expressed through descriptive prompts rather than predefined algorithmic modeling. Unlike conventional parametric workflows that require fixed optimization criteria, AI-generated automation functions as a dynamic system, enabling users to engage with computational design without direct scripting intervention.

AI-driven design follows a structured yet flexible process (Figure. 5). The generative system translates abstract design intent into computationally generated forms, which remain interactive and adaptable. Users—including those without technical expertise—can refine and reconfigure design outcomes through intuitive interfaces, replacing predefined parametric controls with real-time interaction. This process extends beyond digital modeling: AI-to-robotic fabrication workflows ensure a seamless transition from AI-generated forms to manufacturable outputs, embedding design automation into scalable production systems.

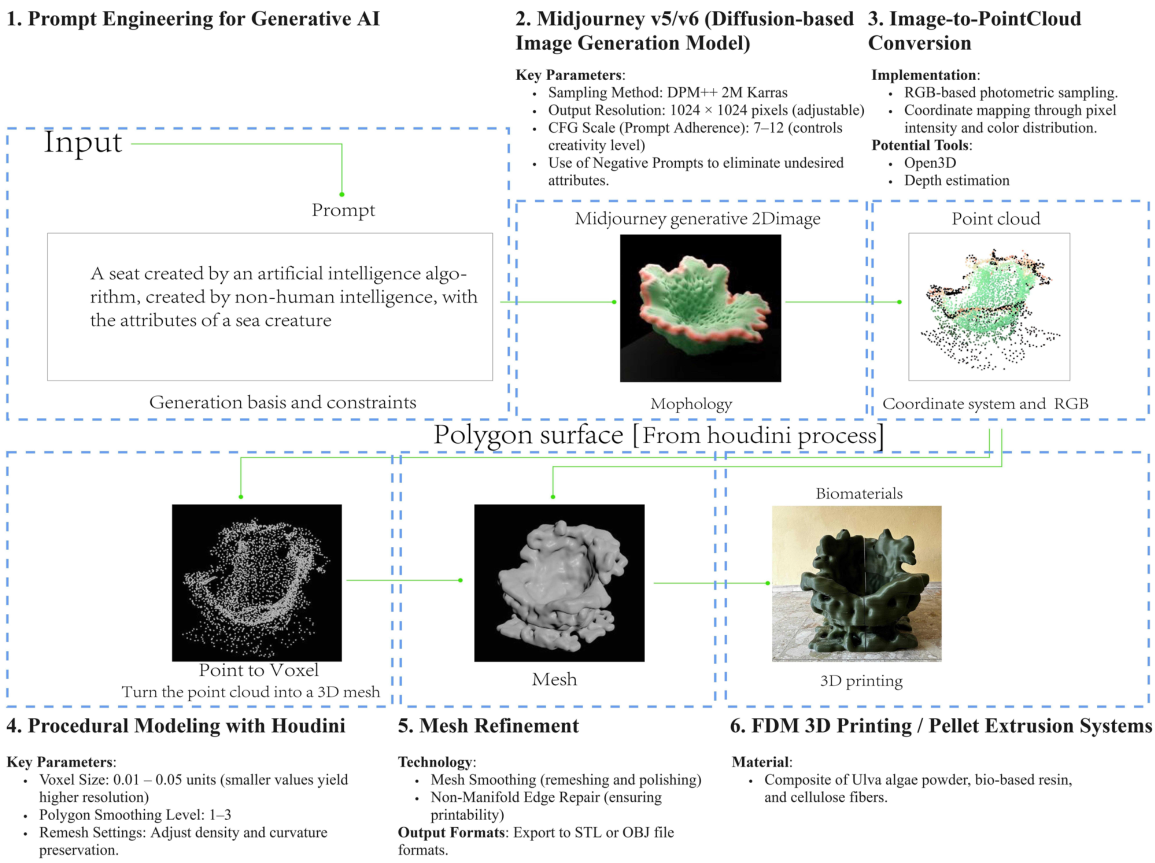

Figure 5. AI Design Workflow diagram, image by Author and Boliu

Unlike conventional computational design, which requires extensive algorithmic refinement and manual intervention, AI-driven automation democratizes generative design by embedding real-time form-finding processes into an accessible workflow. As illustrated in (Fig. 6), the iterative evolution of AI-generated coral-inspired chairs highlights how designers shift from direct form-makers to interactive participants in generative systems. AI does not merely optimize predefined geometries but enables a dynamic negotiation between human input and computational intelligence, fostering emergent forms that respond to structured prompts, environmental constraints, and material conditions.

The iterative design process demonstrates how AI facilitates controlled variation and design flexibility, where subtle parameter adjustments lead to significant morphological transformations (Figure. 6). This evolution is not purely stochastic; rather, it can be refined through vocabulary-based prompt engineering and structured control mechanisms, ensuring that generated models align with specific aesthetic, structural, and functional requirements. Additionally, AI tools such as ControlNet allow for fine-tuned parameter adjustments, refining volumetric articulation, material thickness, and surface characteristics with precision and coherence.

This automation broadens the applicability of generative design by eliminating the need for direct scripting and algorithmic control, allowing users to engage with AI-generated spatial formations through intuitive interfaces rather than complex programming. It enables design flexibility through vocabulary-based control, where subtle linguistic inputs influence form variations, as demonstrated in (Figure. 6) by the evolution from smooth to high-density, angular coral-like structures. Additionally, AI tools such as ControlNet introduce fine-tuned parameter control, facilitating precise adjustments to geometry, density, and textural articulation while maintaining design coherence. Finally, this process automates the translation from conceptual input to manufacturable form, ensuring that computationally generated structures can be directly fabricated with minimal post-processing through AI-integrated additive manufacturing workflows.

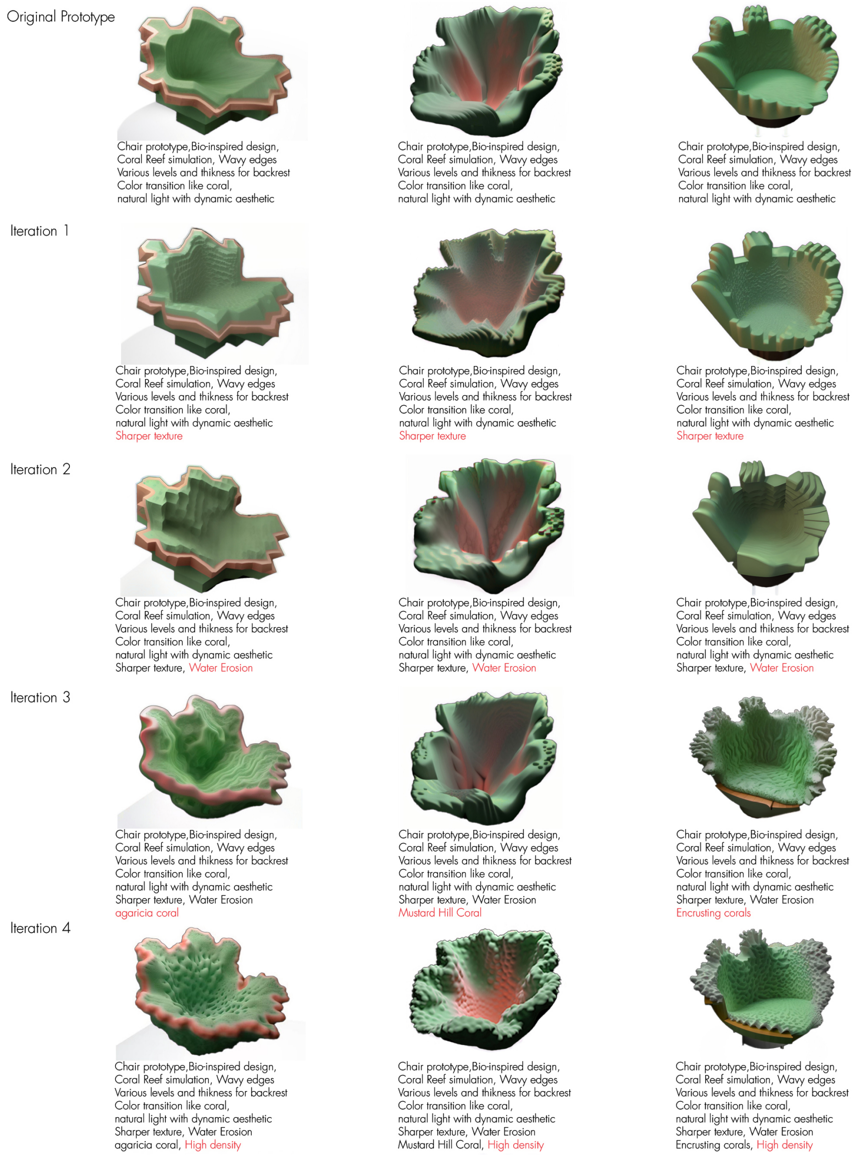

Figure 6. Design Iteration based on Prompts Changes, Image by Author and Bo Liu

The transition from object-scale AI generative design to urban-scale adaptation aligns material intelligence with fabrication scalability. AI-driven algorithms first analyze bio-based material properties, optimizing morphologies for structural performance and ecological adaptability. Unlike traditional bio-design, which manually translates material research into design, AI enables a seamless, automated synthesis, embedding material intelligence directly into computational workflows.

As AI integration advances, the shift from digital models to large-scale robotic fabrication becomes more fluid. Robotic extrusio allows AI-generated forms to be materialized directly, minimizing waste and human intervention while optimizing material distribution and structural complexity (Figure. 7). The robotic fabrication system employed a modified pellet extrusion mechanism, operating with a nozzle diameter of approximately 3 mm and a printing speed between 20–50 mm/s. Material consumption rates averaged 600–800 grams per square meter of fabricated surface, depending on the complexity and density of the mesh. Scaling feasibility tests demonstrated the system's ability to produce components up to 2 meters in height within a continuous 24–36 hour printing window, supporting the viability of urban-scale bio-digital construction. This process does not just generate aesthetic forms but also informs construction methodologies that dynamically respond to material constraints and fabrication logic.

Figure 7. Robotic Fabrication Process of AI Algae Chair, Photos by Author

With robotic construction, AI-driven designs extend beyond prototyping into infrastructural and architectural applications. AI operates within real-time feedback loops, continuously adjusting morphologies to fabrication parameters and site-specific conditions. This adaptability marks a shift where digital intelligence directly informs material logic, establishing a fluid exchange between computational design, bio-material adaptation, and fabrication.

Looking ahead, AI will move beyond design augmentation to become an active agent in material innovation and construction. Its ability to scale from object-based interventions to architectural systems redefines the relationship between generative design and digital fabrication. As technology evolves, AI's capacity to synchronize algorithmic form generation, material constraints, and robotic execution will further shape adaptive, ecologically responsive built environments.

2.3. AI as a Systemic Urban Intelligence: Synthetic Morphologies and the Evolution of Algae City

AI-driven material intelligence has evolved from an optimization tool into an active participant in urbanism. No longer confined to refining predefined structures, AI continuously negotiates ecological, infrastructural, and socio-political dynamics, recalibrating spatial configurations in response to environmental flux and material agency. Within this framework, Algae City is not a static urban project but a computationally adaptive ecosystem, where spatial formations emerge from AI-mediated material interactions rather than rigid master planning. The challenge is no longer how to optimize a design but how to establish a large-scale, evolving intelligence system, where AI, ecological networks, and material performance interact to shape new urban paradigms (Weinstock, 2010). By embedding AI as an agent of spatial formation, urban materiality ceases to be deterministically planned and instead emerges through bio-computational processes that respond to real-time conditions. For example, AI-based adaptive coastal defense systems could continuously reorganize algae-derived modular structures along Qingdao's shores in response to shifting hydrodynamic and sedimentation patterns. Similarly, dynamic zoning strategies could be implemented within flood-prone urban areas, allowing algae-integrated infrastructures to adjust based on real-time environmental and socio-economic datasets.

The potential of AI in urban morphogenesis is demonstrated in GAN-Physarum La Dérive Numérique (Pasquero & Poletto, 2023), where neural networks trained on non-neuronal intelligence optimize spatial formations through continuous environmental interaction. Instead of enforcing fixed spatial arrangements, these systems engage in dynamic negotiations with urban metabolism, forming a synthetic intelligence that co-evolves with its material and climatic conditions. This transition marks a shift from AI as a passive optimization mechanism to an active force in urban formation, leading to the emergence of fully AI-mediated morphogenetic landscapes.

This logic is central to Algae City, where AI-generated spatial morphologies emerge through multi-scalar environmental feedback loops and adaptive material processes. The coastal transformations of Qingdao exemplify this approach, as architectural interventions cease to be fixed formal entities and instead respond dynamically to hydrodynamic forces, sedimentation cycles, and algae bloom patterns (Zhang et al., 2019). Computational experiments explore AI's capacity to redefine Qingdao's urban identity, from historical monument reinterpretations to large-scale synthetic landscapes. Figures 8–11 presented here are conceptual visualizations intended to demonstrate design possibilities; they have not yet undergone detailed engineering validation or structural feasibility testing. Future work aims to transition selected prototypes toward technical realization through performance simulations and material prototyping.

The first transformation investigates AI-generated adaptation of historical landmarks, where morphogenetic computation reconfigures Qingdao's urban monuments into algorithmically evolving entities (Figure. 8). The 54 Square Monument, traditionally a fixed spatial artifact, is reinterpreted as a biologically informed structure, recalibrated through synthetic ecologies that respond to atmospheric and urban fluctuations. This challenges conventional preservation strategies, which assume cultural identity must be static (Carpo, 2017), proposing instead that monuments evolve through computational adaptation.

Figure 8. AI Generative Algal Urban Form1 - Urban Statue

Beyond reconfiguring individual landmarks, AI-driven morphogenetic processes reshape Qingdao's coastal landscapes (Figure. 9). Rather than relying on master-planned urbanism, morphogenetic algorithms generate self-adjusting spatial systems based on ecological and climatic data. AI-driven simulations of algae bloom patterns inform hydrodynamic-responsive structures, replacing rigid flood-control barriers with soft, adaptive ecologies that continuously reconfigure in response to tidal flux, erosion cycles, and sedimentation dynamics (Pasquero & Poletto, 2023). This transition mirrors natural evolutionary processes, where form emerges through bio-digital negotiations rather than imposed planning (Benyus, 1997).

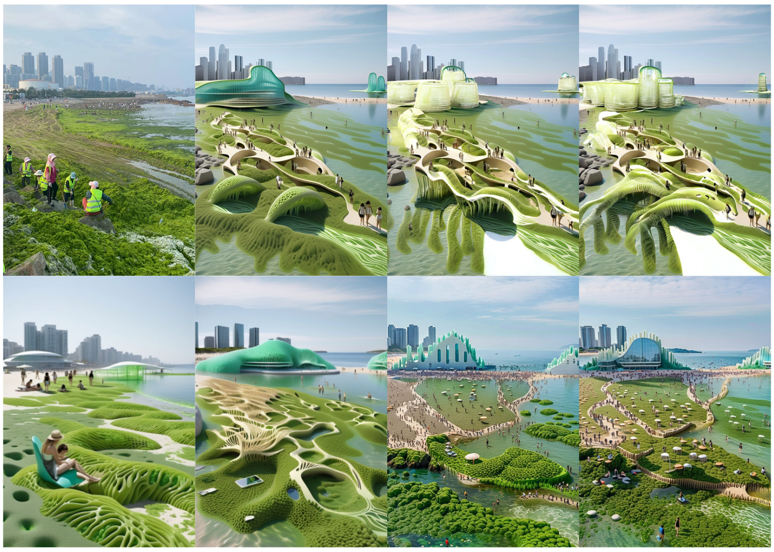

Figure 9. AI Generative Algal Urban Form 2 - Costal Landscape

AI's integration into algae-based material processing further expands this framework, where synthetic morphologies emerge at the intersection of computational fabrication, agricultural cycles, and decentralized production. The transition from algae as ecological waste to infrastructural material signals a fundamental departure from traditional waste management, where AI does not simply optimize an existing process but constructs a new model of bio-digital materiality. The robotic fabrication of algae-based structure demonstrates how material intelligence is no longer constrained by industrial production models (Figure. 10), instead functioning as an adaptive computational system (Menges, 2012). Unlike fixed material economies that depend on static supply chains, AI-generated algae infrastructures operate as metabolic systems, where material cultivation, processing, and fabrication exist within an automated feedback loop.

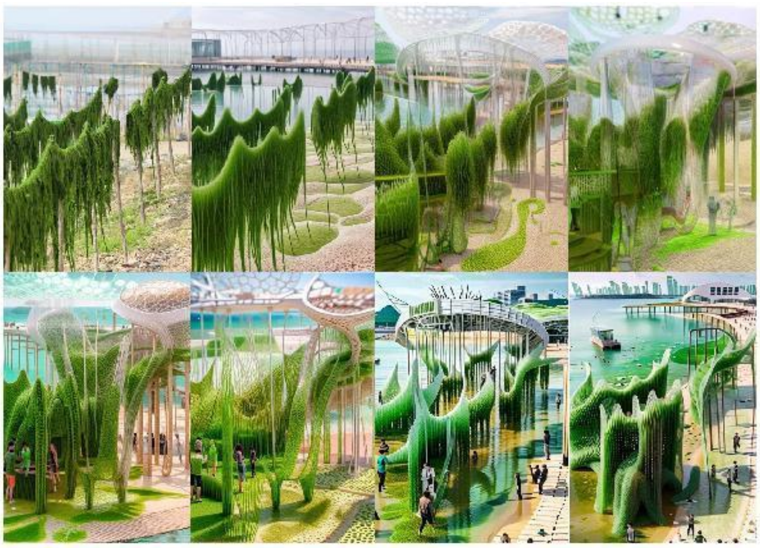

Figure 10. AI Generative Algal Urban Form 3 - Algae Transforming Infrastructure

As AI morphogenetic processes scale from material systems to urban formations, the relationship between synthetic ecology and computational urbanism becomes increasingly evident. AI-generated landscapes shift away from traditional infrastructural planning toward self-regulating urban formations (Figure. 11), offering an alternative model for coastal resilience. In this model, cities no longer rely on static engineering solutions but evolve in response to environmental contingencies, including tidal flux, erosion cycles, and sedimentation dynamics (Negroponte, 1970). The distinction between artificial and natural landscapes blurs, as AI-generated urbanism does not simply mimic biological systems but actively integrates them into computational spatial evolution.

Figure 11. AI Generative Algal Urban Form 3 - Algae Transforming Infrastructure

Beyond redefining urban typologies, AI-driven design transforms participatory urbanism, making computationally generated morphologies an open-source framework for city-making. By embedding participatory AI interfaces in Algae City, citizens and policymakers directly engage with synthetic morphogenetic processes, allowing urban transformation to emerge as an iterative, collective intelligence. This framework not only expands design accessibility but reconfigures urban authorship, shifting control from municipal planning institutions to an adaptive system shaped by environmental data, AI-generated intelligence, and public participation. In this model, urban branding is no longer a curated narrative but an algorithmically emergent identity that continuously recalibrates through computational self-regulation.

The significance of AI in Algae City is not just its ability to generate architectural forms, but its capacity to construct an entirely new model of urban intelligence, where branding is not imposed but algorithmically emergent. Unlike previous urban identity models—structured around industrial frameworks or cultural appropriation—Algae City introduces a computational branding paradigm, where identity is not curated but continuously recalibrated through material flows, social interactions, and ecological contingencies. This shift from optimization-based AI to generative intelligence marks a fundamental epistemological transition: Algae City is not an experimental project but an urban system where computation, ecology, and materiality converge into a self-regulating coastal brand. AI does not just optimize Algae City—it generates it.

3. Algae City as Brand – From Pollution to URBAN IDENTITY

3.1. From Waste to Urban Capital: A New Paradigm for Algae City

Urban identity has historically been shaped by the materials that define a city's industrial, cultural, and ecological landscape. Whether it is Florence's Carrara marble, Detroit's automotive industry, or Guiyu's e-waste processing economy, cities have long been characterized by the resources they extract, manufacture, or discard. In each case, waste is not merely an environmental byproduct—it is an economic and semiotic agent that can either reinforce a city's decline or serve as the foundation for a new urban paradigm. The transformation of waste into capital requires not only material reintegration but also a shift in public perception, economic structures, and cultural systems that support it (Lepawsky, 2018).

Building on this premise, Algae City redefines Qingdao's urban identity by transforming the traditionally perceived pollutant—Ulva algae—into a computationally generated urban fabric. However, unlike previous waste-to-brand transformations that relied on industrial adaptation, as seen in Guiyu, or cultural repositioning, as exemplified by Berlin's graffiti scene, Algae City introduces a model in which AI-generated synthetic morphologies continuously construct and adapt the city's identity. This departure from historical precedents sets it apart from two major urban transformation models.

E-Waste City, such as Guiyu in China, relies on industrial-scale material repurposing, integrating discarded electronics into global supply chains. While this model successfully repositions waste within an economic framework, it remains bound to a linear economic structure in which waste is continuously processed rather than fundamentally redefined. The transformation, though functional, does not challenge the perception of waste as an externality; instead, it perpetuates its presence through extraction and repurposing mechanisms. In contrast, Graffiti City, exemplified by cities like Berlin, São Paulo, and New York, achieved urban rebranding through cultural legitimization. Street art, once considered vandalism, was absorbed into the visual economy, turning what was previously a mark of disorder into an aesthetic and commercial asset. However, this transformation was aesthetic rather than material, requiring social acceptance rather than ecological reintegration.

Algae City moves beyond both of these models. Unlike Guiyu, which remains dependent on waste influx and industrial labor, Algae City generates a metabolic urban model in which algae is not simply processed as a raw material but structurally embedded into urban systems through AI-driven synthesis. Unlike Berlin's graffiti culture, which required societal acceptance and municipal endorsement to evolve into a recognized brand, Algae City operates autonomously through AI-driven material intelligence, ensuring continuous evolution without the need for human cultural approval. This approach fundamentally redefines urban waste management by integrating computational design, ecological intelligence, and urban branding into a self-sustaining framework. By embedding AI as an active agent in both material transformation and identity formation, Algae City transcends conventional waste-to-resource narratives, positioning algae as a dynamic force that recalibrates Qingdao's urban and ecological metabolism in real time.

However, while Algae City proposes a computationally self-evolving urban identity, its implementation would face significant policy challenges. One major concern is data governance: determining who controls, accesses, and regulates the environmental and urban data streams that feed into AI-driven morphogenetic systems. Another challenge lies in the maintenance and stewardship of algae-integrated infrastructures—questions of ownership, funding responsibilities, and lifecycle management would require innovative public-private governance models. Finally, the traditional regulatory frameworks designed for static urban environments may struggle to accommodate the dynamic, continuously evolving forms generated by AI. Addressing these challenges will be crucial for translating the Algae City vision into a functional and resilient urban reality.

3.2. Computational Branding: How Algae City Constructs a Self-Adaptive Identity

Traditional urban branding follows two primary trajectories: industrial repurposing, as seen in Guiyu's transformation through e-waste recycling, and cultural reframing, as exemplified by Berlin's graffiti scene evolving into an urban identity. While these models demonstrate the potential for waste or subversive practices to be repositioned as economic and cultural assets, they remain constrained by either labor-intensive industrial processes or socially mediated acceptance. Algae City introduces a third pathway—an AI-generated, continuously evolving identity—that does not depend on external market forces or cultural approval but is embedded within the city's computational metabolism.

The integration of electronic waste into Guiyu's economic infrastructure demonstrates how discarded materials can transition from pollutants to economic drivers. Initially, Guiyu's e-waste industry was defined by informal processing networks, where unregulated dismantling operations led to severe environmental degradation (Mujezinovic, 2019). Over time, the city developed a structured recycling economy, embedding electronic waste into a larger material network that facilitated its reintegration into global supply chains (Lepawsky, 2018). Despite its industrial success, Guiyu's transformation remained contingent upon labor-intensive processes and large-scale material extraction, reinforcing an economic model where waste was not eliminated but continuously cycled through extractive frameworks (Mujezinovic, 2019).

The recontextualization of street art as a cultural and economic asset in cities like Berlin and São Paulo represents another trajectory, where a previously marginalized practice was redefined as an essential component of urban identity. Once regarded as an urban nuisance, graffiti was absorbed into municipal branding strategies, gaining recognition through legalized street art districts, curated exhibitions, and tourism-based economies (Iveson, 2010; Young, 2013). While this transformation shifted graffiti from an act of resistance to a recognized urban aesthetic, its success relied on cultural legitimization rather than material integration. Unlike e-waste, which was absorbed into industrial economies, graffiti's incorporation into the urban fabric depended on shifting social perceptions, municipal endorsement, and the commodification of subversive visual culture.

Algae City diverges from both of these models by removing dependency on human labor, market-driven repurposing, or social validation. Unlike Guiyu, which remains tied to extractive economic cycles, Algae City circumvents traditional material processing through AI-driven metabolic transformations, embedding algae directly into the urban system as a generative resource. Unlike Berlin's graffiti culture, which required a shift in social perception before gaining economic legitimacy, Algae City's identity is algorithmically emergent, continuously adapting through computational intelligence rather than human endorsement. This distinction marks a fundamental shift in urban branding—one in which identity is no longer a curated or imposed construct but a self-sustaining computational system that recalibrates itself in response to ecological, material, and technological flux (Table 1).

Table 1. Comparative Analysis of Urban Branding Strategies: E-Waste City, Graffiti City, and AI-Generated Algae City

Criteria	E-Waste City (Guiyu, China)	Graffiti City (Berlin, São Paulo, NYC)	Algae City (Qingdao, AI-Generated)
Material Treatment	Downcycling waste into global supply chains	Visual reinterpretation rather than material use	Structural transformation of algae into synthetic landscapes
Economic Model	Labor-intensive extraction industry	Tourism, art economy, municipal funding	Computational metabolism, regenerative material cycles
Public Engagement	Limited; industry-driven workforce	High; citizen-led creative interventions	AI-mediated participatory urbanism
Adaptability Over Time	Static; dependent on waste influx	Tied to cultural trends and city planning	Algorithmically adaptive, evolving brand

4. Discussion and Conclusions

Urban identity has long been shaped by material economies, technological shifts, and cultural narratives—from Detroit's industrial consolidation to Florence's marble-driven aesthetic economy and the computational morphogenesis of contemporary smart cities. Traditionally, branding has been imposed top-down through planning structures or bottom-up through cultural re-appropriation, reinforcing a dialectical relationship between urban form and socio-economic constructs (Zukin, 1989). Algae City disrupts this paradigm, introducing a third model: a computationally emergent brand that is neither designed nor curated but algorithmically self-generating.

This shift challenges the notion that urban identity is a fixed semiotic system governed by human-centered design. Instead, it proposes an alternative framework where material intelligence, bio-computation, and AI-driven spatial morphogenesis act as the primary agents of urban formation. Unlike historical branding models that relied on economic integration (E-Waste City) or cultural recognition (Graffiti City), Algae City is autonomous, continuously recalibrated through computational negotiation with its ecological and urban surroundings.

4.1. From Optimization to Self-Generation

For decades, computational design has been understood through optimization, where algorithms enhance efficiency, refine form, or maximize material performance (Schumacher, 2020). The advent of AI-driven morphogenetic systems marks a new ontological condition—where computation is no longer just a design tool but an agent of spatial evolution. Carpo (2017) distinguishes this shift as the second digital turn, where AI challenges authorship, control, and formal determination, moving beyond parametric customization to self-generating design intelligence. This transformation is central to Algae City, where the designer is no longer the sole author of urban identity, but a mediator within an AI-generated metabolic system. Branding ceases to be a static representation imposed upon the city and instead emerges as an evolving intelligence, independent of human intervention. This aligns with Leach's (2021) argument that AI must be understood not as a tool but as a cognitive system capable of generating novel spatial conditions beyond human bias.

4.2 AI-Driven Urban Intelligence

Algae City is more than an urban prototype—it challenges the foundations of urbanism, governance, and spatial authorship. Unlike past models where waste gained economic value (Guiyu) or cultural legitimacy (Berlin's street art districts), Algae City requires no external validation—its identity self-regulates through computational branding. Unlike traditional branding, which operates within fixed parameters, Algae City establishes a computationally adaptive urbanism, where branding emerges through recursive generative algorithms that respond to environmental, social, and technological contingencies (Negroponte, 1975). By embedding AI-generated morphogenetic processes into urban metabolism, Algae City shifts branding from an external representation to an intrinsic intelligence, redefining urban identity not as a symbol but as a self-regulating algorithmic phenomenon.

4.3 Adaptive Computational Urbanism

Algae City is more than an urban prototype—it challenges the foundations of urbanism, governance, and spatial authorship. Unlike past models where waste gained economic value (Guiyu) or cultural legitimacy (Berlin's street art districts), Algae City requires no external validation—its identity self-regulates through computational branding. Unlike traditional branding, which operates within fixed parameters, Algae City establishes a computationally adaptive urbanism, where branding emerges through recursive generative algorithms that respond to environmental, social, and technological contingencies (Negroponte, 1975). By embedding AI-generated morphogenetic processes into urban metabolism, Algae City shifts branding from an external representation to an intrinsic intelligence, redefining urban identity not as a symbol but as a self-regulating algorithmic phenomenon.

4.4 Implications for Design, Ecology, and AI

This transition forces a fundamental rethinking of architectural and urban practice. If branding is no longer curated but computationally emergent, what becomes the role of the designer in an AI-generated city? If planners are no longer urban authors but observers within a self-generating system, how does governance interact with autonomous urban intelligence?

These questions align with the broader post-anthropocentric shift in design, where the role of architects is not to impose form but to facilitate emergent systems. Weinstock (2010) argues that biological and computational intelligence follow the same evolutionary logic, requiring architecture to move from designing objects to designing adaptive ecologies.

Ecologically, Algae City presents a new model of bio-computational intelligence, where urban metabolism is no longer driven by linear extraction and waste production but by closed-loop, self-regulating material cycles. It extends Cradle to Cradle principles (McDonough & Braungart, 2002), yet transcends sustainability—AI-generated morphologies autonomously recalibrate material and ecological flows.

4.5 The Future of AI-Generated Branding

If past urban identities were shaped by economic shifts, industrial cycles, or cultural narratives, Algae City establishes a new precedent—one where identity is computationally emergent, algorithmically self-sustaining, and entirely synthetic. This shift challenges fundamental assumptions about urban authorship, raising critical questions: What role remains for human designers, planners, and policymakers if urban identity can be AI-generated? If branding is no longer culturally constructed but an emergent algorithmic process, does urban identity become detached from historical precedent? What are the socio-political implications of AI-generated branding in governance, spatial equity, and public engagement?

As Algae City continues to evolve, it represents not just a material intelligence experiment but a radical shift in how cities define themselves through computation. No longer constrained by static representations, pre-determined master plans, or curated branding strategies, it marks the dawn of an era where AI does not optimize cities—it generates them. Qingdao does not define Algae City—Algae City defines Qingdao

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