Journal of Marine Science and Engineering

Review

Engineering Perspectives on Kelp (*Saccharina japonica*) Cultivation Structures in China: Nearshore Practices and Transition to Offshore Environments

Chenxuan Huang [1,2], Huu Phu Nguyen [1,2], William Lindsey White [3] and Chien Ming Wang [1,2,*]

1 School of Civil Engineering, The University of Queensland, St Lucia, QLD 4072, Australia; chenxuan.huang@uq.edu.au (C.H.); huuphu.nguyen@uq.edu.au (H.P.N.)
2 Australia Blue Economy Cooperative Research Centre, Launceston, TAS 7248, Australia
3 School of Science, Auckland University of Technology, Auckland 1010, New Zealand; lindsey.white@aut.ac.nz
* Correspondence: cm.wang@uq.edu.au

Abstract

China produces approximately 91.5% of the world's *Saccharina japonica* (the species denoted by "kelp" herein) and its kelp farms collectively constitute one of the largest populations of floating marine structures anywhere. This review examines them as marine structures rather than as crops, asking what their geometry, load paths and standardization status imply for mechanization and for survival offshore. Nearshore cultivation rests on a single structural family, the floating single line, whose three variants, namely, horizontal, vertical and one-dragon kelp rope raft culture, differ in how the grow-out rope attaches to the backbone rather than in load path or design basis. Of these, the one-dragon configuration is the most promising for offshore adaptation, though on qualitative rather than measured grounds. The principal barrier to mechanized harvesting lies not in harvesting machinery but in a rope geometry dimensioned for manual operation and lacking standardized parameters. Integrated multi-trophic aquaculture, treated here as a structural modification of the kelp longline rather than as an ecological strategy, substantially increases suspended loading without any reported reinforcement of backbone, mooring or buoyancy. Recent offshore projects in Fujian and Shandong prove to be seaward extensions of nearshore rafts rather than purpose-designed systems, in contrast to international programmes which, although pre-commercial, begin from a stated design environment and return verifiable outcomes. We conclude that the defining obstacle to both mechanization and offshore expansion is the cultivation structure itself, and identify mechanization-compatible, load-verified structural standards as the critical and currently unaddressed research priority.

Keywords: kelp nearshore cultivation; mechanization; IMTA; offshore aquaculture

Check for updates

Academic Editor: Azizur Rahman

Received: 20 August 2026
Revised: 22 September 2026
Accepted: 24 September 2026
Published: 27 September 2026

1. Introduction

Seaweeds have a long history of human use, particularly in East Asia, where they have been harvested and cultivated for food, hydrocolloids, animal feed, fertilizers and a wide range of other products [1,2]. Over recent decades, seaweed production has expanded dramatically and has shifted overwhelmingly towards aquaculture. In 2024, global farmed seaweed production reached approximately 38.8 million tonnes wet weight, with China producing approximately 24.3 million tonnes, or 62.6% of the global total [3]. The scale of modern production contrasts strongly with the industry described at the end of the twentieth century, when approximately 7 million tonnes wet weight of seaweeds were cultured globally and production was already strongly concentrated in China, Korea and Japan [2].

Although China cultivates a diverse range of red, green and brown seaweeds, production is concentrated in a relatively small number of taxa. In 2024, the principal cultivated seaweeds on mainland China were *S. japonica* (12.58 million tonnes), *Gracilaria* spp. (6.20 million tonnes), *Undaria pinnatifida* (2.31 million tonnes) and *Porphyra* spp. (2.09 million tonnes), with additional production of *Sargassum fusiforme* and other brown seaweeds [3]. *S. japonica* and *U. pinnatifida* together accounted for approximately 14.9 million tonnes of Chinese aquaculture production in 2024. China produced approximately 91.5% of global *S. japonica* and 79.1% of global *U. pinnatifida* production in that year, illustrating the extraordinary concentration of global kelp aquaculture within China [3]. The development of this industry has been rapid. Earlier assessments of world seaweed utilisation documented China as the dominant producer of *Laminaria* (now principally reported as *Saccharina*) by the mid-1990s, while Chinese *Undaria* production remained relatively small [2]. By 2012, Chinese production had increased to 4.90 million tonnes of *Laminaria*/*Saccharina* and 1.75 million tonnes of *U. pinnatifida* [1]. By 2024, these values had increased to 12.58 and 2.31 million tonnes, respectively [4].

S. japonica and *U. pinnatifida* both belong to the order *Laminariales* and are together referred to as “kelps” in much of the open literature. In Chinese industry usage, however, “kelp” denotes *S. japonica* specifically, while *U. pinnatifida* is a distinct crop with different cultivation practice. Because the cultivation structures reviewed here are those developed for *S. japonica*, the term “kelp” is used herein to mean *S. japonica* alone; *U. pinnatifida* is referred to by name where its production statistics are cited for context. The continued expansion of kelp cultivation reflects both sustained demand for seaweed biomass and major advances in hatchery production, selective breeding, cultivation systems, farm management and processing. Seaweeds produced in China support established food and hydrocolloid industries and are increasingly considered as feedstocks for biostimulants, animal feeds, biomaterials, biorefineries and other higher-value products. Large-scale seaweed cultivation also provides ecosystem services through the uptake of dissolved nutrients and carbon and has become an important component of integrated multi-trophic aquaculture in several Chinese coastal regions [5,6].

The emergence of China as the world’s dominant kelp producer is closely linked to the development of cultivation technology and engineering. *S. japonica* is not indigenous to China and was introduced from Japan to the Dalian region during the early twentieth century. Experimental and small-scale raft cultivation subsequently developed, followed by major technical advances, including improved seedling production, southward extension of cultivation and the development of large-scale floating-raft farming systems [5]. *U. pinnatifida* has a different history in China: although small natural populations occur in parts of Zhejiang Province, the stocks now cultivated commercially in Liaoning and Shandong were introduced from Japan, with commercial cultivation developing from the 1980s onwards [5]. Together, these developments established the biological and technical foundation for the modern Chinese kelp industry.

Kelp aquaculture is now distributed along much of China’s eastern coastline, from warm-temperate and subtropical production regions in the south to major temperate farming areas in Shandong and Liaoning in the north [4], Figure 1 shows the three Chinese provinces (Liaoning, Shandong and Fujian) where the major kelp farms are located. Kelp production is particularly important in the northern and central coastal provinces, although kelp cultivation has also been successfully extended southwards into Fujian through the development of appropriate strains and cultivation practices [5]. The very large scale of production has required cultivation systems that are inexpensive, robust and capable of supporting high biomass densities, while also permitting increasingly efficient deployment, farm management and harvesting. Consequently, the development of the Chinese kelp industry has been accompanied by progressive innovation in farm structures and, more recently, increasing mechanization and interest in expansion into more exposed offshore environments.

A recent global review by Khan et al. [7] shares our aim of mapping the opportunities and innovations in macroalgae farming but approaches the subject from a worldwide perspective, emphasizing the potential value of macroalgal cultivation in addressing climate change, emerging development trends in the sector, and the biotic and abiotic constraints it faces. The present review is complementary rather than overlapping since we focus on the farming systems and configurations of kelp farming in China (particularly *S. japonica*) and examine the engineering considerations involved in its transition from nearshore to offshore cultivation.

This review focuses on the engineering dimensions of kelp aquaculture in China, where two circumstances make a structural re-examination timely. The first is scale: China produces 91.5% of global *S. japonica*, so its raft systems collectively constitute one of the largest populations of floating marine structures in the world, yet their principal dimensions, mooring arrangements and component specifications remain experience-based and regionally idiosyncratic rather than derived from defined design conditions. The second is that both pressures now bearing on the industry are structural rather than biological: mechanized harvesting is constrained not by machine capability but by a rope network whose geometry was fixed by the requirements of manual operation, while the policy-driven relocation of farms seaward exposes structures designed for sheltered bays to significant wave heights of up to 4 m and current velocities approaching 0.9 m/s. The structural literature has not kept pace, leaving four specific gaps. (i) Nearshore raft structures: Hu et al. [5,7] and Liu et al. [7] describe the raft structures used in China but classify them by culture method rather than by structural behavior; none have been examined in terms of structural complexity, mechanization potential, resistance to currents and waves, or applicability offshore. (ii) Mechanization: Hong et al. [8] surveyed Chinese kelp-harvesting vessels comprehensively and analyzed the machinery. What the cultivation infrastructure demands of, and denies to, a harvesting machine has not been adequately addressed. (iii) Structural implications of IMTA: Kelp-based integrated multi-trophic aquaculture has been reviewed extensively for its ecological function and economic performance [9–17], but the longline that carries it is treated as a setting rather than as a loaded structure; the hydrodynamic loading of suspended co-culture units, characterized in detail for mussel farms, has never been applied to kelp-based IMTA in China or elsewhere (Section 3.3). (iv) Offshore structural design: Reviews of offshore aquaculture structures [18–23] address chiefly fish cages and non-Chinese seaweed projects, while China's offshore seaweed programmes are documented mainly in industry and policy sources. There has hitherto been no critical engineering assessment of these purpose-designed offshore seaweed cultivation structures or incremental adaptations of nearshore rafts. This review addresses the first two gaps in Section 2, the third gap in Section 3, and the fourth gap in Section 4.

https://doi.org/10.3390/jmse14191794

(**a**) **Three kelp-farming provinces in China—Liaoning, Shandong and Fujian**

(**b**) **Locations of kelp farms in Liaoning**

(**c**) **Locations of kelp farms in Shandong**

(**d**) **Locations of kelp farms in Fujian**

Figure 1. Major kelp-farming provinces—Liaoning, Shandong and Fujian—and coastal areas where kelp farms are located.

https://doi.org/10.3390/jmse14191794

2. Nearshore Kelp (*S. japonica*) Cultivation Structures and Mechanization

2.1. Structures for Nearshore Kelp Cultivation

In China, kelp aquaculture can be traced back to the period between 1914 and 1925, when Otsuka Yoshiro introduced *S. japonica*, an edible kelp species from Hokkaido to Dalian. He was responsible for designing the earliest raft cultivation scheme that was put into practical use in the early 1940s [5]. Nowadays, various types of floating rafts represent the most efficient method of seaweed cultivation and are mainly used for shallow-sea seaweed farming [7]. Floating raft cultivation is also the primary method used in the kelp farming industry in China [5,7,8,24–26].

The most fundamental structure of the floating raft infrastructure used in kelp cultivation is a baseline floating main rope structure known as the single-line structure, from which all subsequent structural variations are derived. As illustrated in Figure 2, this single-line structure mainly consists of one backbone rope, two mooring ropes, two wooden stakes (or weighted anchors), and several buoys attached to the backbone [5,7,26,27]. The length of the backbone is usually 60 m to 100 m, depending on the region and the magnitude of wind and wave conditions [7,26]. The backbone length can be appropriately adjusted according to local conditions; it can be shortened under stronger wind and wave actions and can be lengthened under milder conditions [7,26]. The backbone and the mooring rope are generally made of synthetic fiber materials such as polyethylene, with diameters typically ranging from 15 mm to 30 mm, corresponding to working loads of approximately 4 kN to 15 kN [8]. The length of the mooring rope is about twice the water depth. In sea areas with stronger wind and waves, the rope length is increased to 2.5 to 3 times the water depth [5,7]. In traditional Chinese kelp cultivation, the anchoring method for the single-line structure generally employs wooden stakes driven into the seabed, using hard wood with a diameter of 15 cm to 25 cm and a length of 1.5 m to 2.5 m, driven into the shallow-sea seabed as the anchoring method [7]. In addition, in sea areas where stake-driving is not feasible, weighted anchors of 3 tons to 6 tons are used as the anchoring method instead [7]. In practice, the choice of floats is not standardized. The floats range from plastic and glass buoys to plastic foam and even discarded plastic bottles; the choice is driven largely by the low cost and ready availability of these materials [5,7].

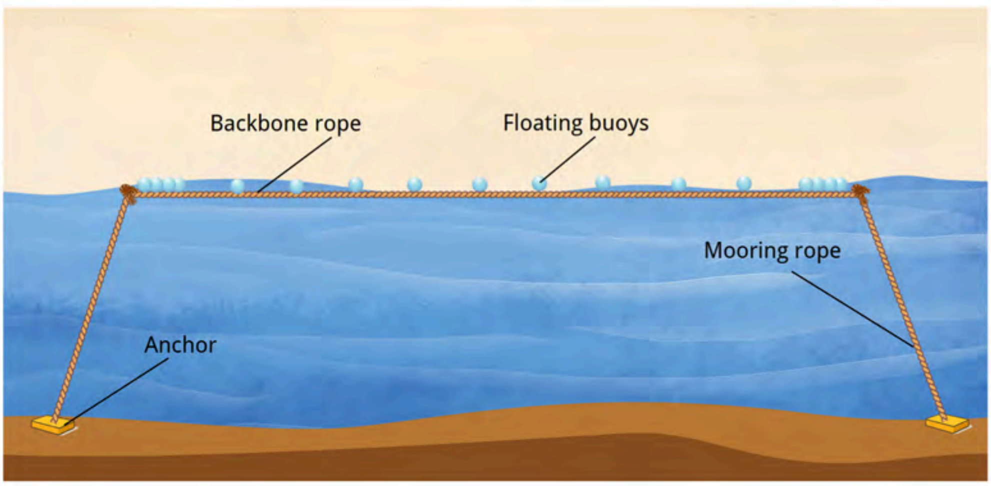

Figure 2. Structure of a floating single-line system.

Production practice has demonstrated that this single-line structure exhibits strong resistance to wind and waves, with minimal impact from wind-driven currents, making it the most widely adopted structure in the current Chinese kelp aquaculture industry [5,7,8,24–26].

During the kelp cultivation process, the kelp is not directly attached to the backbone; instead, the kelp juveniles are attached to a kelp rope in one of several ways: either the spores are directly seeded onto the kelp rope or small plantlets are inserted between the strands of the kelp rope. This kelp rope is suspended from the backbone [8]. The manner in which the kelp rope is connected to the backbone varies considerably. A review of numerous Chinese studies on kelp cultivation structures reveals that the classification of kelp cultivation systems is quite disorganized, with no unified standard. Various categories have been proposed, including single floating rafts, double-frame rafts, square-frame rafts, rectangular-frame rafts, centipede-style raft frames, and submerged raft frames [5,7,8,24–26], among others. In essence, however, the most fundamental structure underlying kelp floating raft cultivation remains the single-line structure shown in Figure 2. The different types of raft configurations described in the literature [5,7,8,24–26] lies in the way the kelp rope is connected to the backbone, together with further structural adjustments (such as submersion). After reviewing a large body of literature, three basic raft culture methods have been identified: the horizontal kelp rope raft culture method, vertical or hanging kelp rope raft culture method, and one-dragon kelp rope raft culture method [28]. In China, the vertical or hanging kelp rope raft culture method is also named the Centipede-style raft culture method by some local farmers. Details of these three raft culture methods are illustrated in Figures 2–4 and explained below.

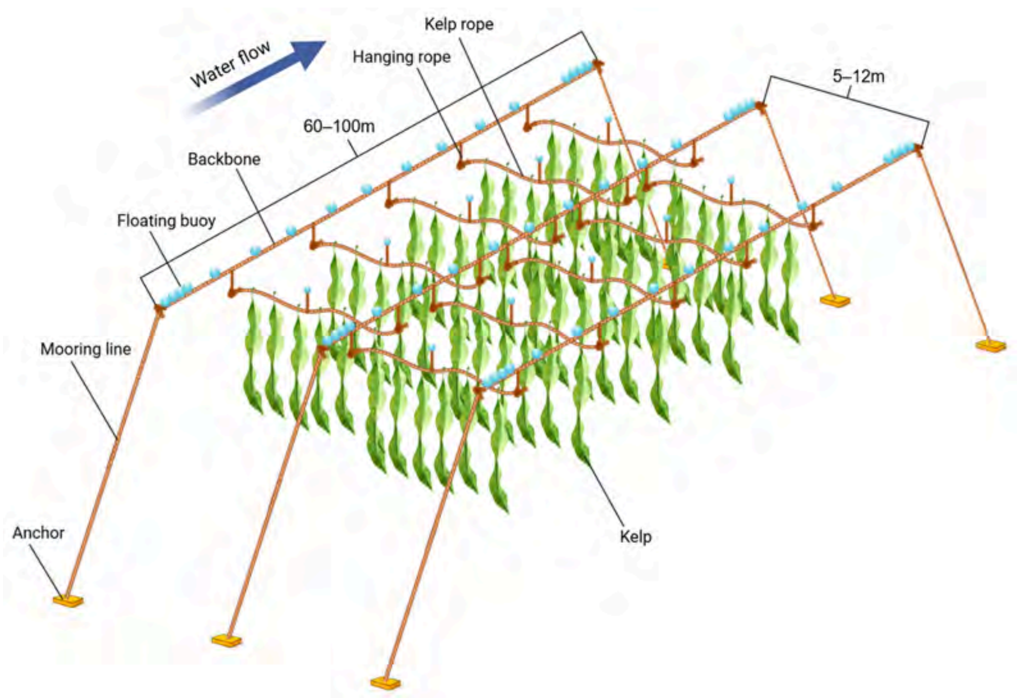

Figure 3. Horizontal kelp rope raft culture method. Kelp ropes are attached in the transverse direction to the backbones.

The horizontal kelp rope raft culture method refers to the method in which the kelp ropes are arranged in transverse direction with respect to backbone in a rectangular grid pattern as shown in Figure 3. The kelp seedlings are evenly distributed along the kelp ropes, forming a continuous "kelp curtain" or "kelp mat," with the hanging depth of the biomass typically not exceeding 3 m [25]. One advantage of the horizontal kelp rope raft culture method is that it provides greater and more uniformly distributed illumination to all kelp plants attached along the kelp ropes. Water currents disperse the blades evenly across the water column, enhancing nutrient exchange and thereby increasing the growth rate of the kelp. In general, the yield obtained from the horizontal kelp rope raft culture method exceeds that of the hanging (vertical) method described below, making it well suited to shallow waters of high turbidity and to nearshore areas characterized by weak currents [29]. A further advantage of the horizontal kelp rope raft culture method lies in its superior structural stability. In deeper waters with stronger currents, the backbones can be shortened to 30–40 m, thereby reducing the total hydrodynamic load acting on the raft system. In addition, the culture ropes deployed under this configuration exhibit smaller oscillation amplitudes under combined wave and current action, and entanglement between adjacent kelp ropes is correspondingly less frequent. The resulting load distribution across the raft is more uniform, and the wave resistance of the system is generally superior to that of the vertical kelp rope raft culture method introduced below [25]. Nevertheless, the horizontal kelp rope raft culture method is not without limitations. Shortly after young sporophytes are transplanted onto the kelp ropes, the excessive irradiance may cause the photophobic holdfasts to detach before they have firmly anchored to the rope, resulting in the loss of juvenile sporophytes [29]. However, the elevated light availability remains beneficial throughout the subsequent growth period of the kelp [29].

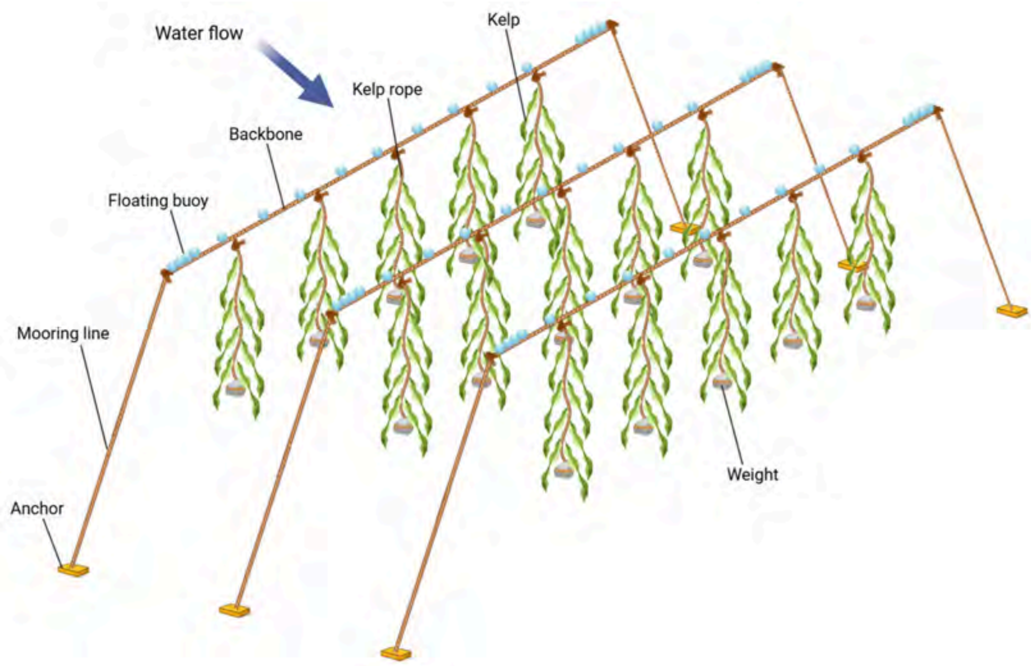

Figure 4. Vertical kelp rope raft culture method. Kelp ropes are attached vertically to the backbones.

In the vertical kelp rope raft culture, the kelp ropes are tied individually to the backbone, and the attached kelp grows along the vertical kelp ropes as shown in Figure 4. The length of individual kelp ropes typically ranges from 5 m to 20 m, with spacing of approximately 0.3 m to 0.6 m between adjacent lines [25]. A stone weight of roughly 0.5 kg is fastened to the lower end of each kelp rope, allowing the rope to sway freely in the water with a pendulum-like motion. During deployment, the backbones should be oriented perpendicular to the prevailing current so that the kelp ropes can move freely with the flow and receive adequate illumination, while entanglement between adjacent ropes is avoided [29]. This arrangement enables effective utilization of the vertical water column; moreover, the rope connection scheme is structurally simple, easy to handle, and comparatively low in cost [29]. However, its drawbacks are equally apparent. Because light intensity attenuates progressively with increasing water depth, the kelp located on the lower portion of the rope is shaded by the plants above and grows markedly more poorly than those at the upper end, with the discrepancy in dry weight yield reaching 24.8–61.6%. Periodic manual reversal of the seeding ropes, estimated at approximately once every two weeks, would introduce additional labour requirements and associated operational costs [30]. Moreover, the blades may sustain a certain degree of physical damage during the reversal process, further reducing overall productivity [29].

The floating single-line system with one-dragon kelp rope raft culture method refers to a configuration in which the kelp ropes lie parallel with respect to the backbones as shown in Figure 5. This design is based on serially connected rafts aligned with the prevailing current direction, also known as a continuous longline configuration [25]. In this arrangement, multiple kelp ropes are connected in series along the dominant flow direction, sharing or partially sharing the backbone. Reinforced anchoring is applied at both ends of the raft rope, while intermediate rafts are allowed to respond flexibly to current-induced motion. Such serial alignment significantly reduces the overall hydrodynamic resistance of the system and lowers the risk of anchor line failure. When compared with horizontal kelp rope raft culture or vertical kelp raft culture method, the one-dragon kelp rope raft culture method exhibits superior engineering stability, is well suited for large-scale deployment, and is highly compatible with mechanized installation and retrieval operations [25]. This cultivation method is particularly applicable to offshore or semi-offshore environments with relatively strong currents and has been increasingly adopted in offshore kelp farming pilot projects in coastal provinces such as Fujian and Shandong, China [7]. In high-sea-state conditions, the one-dragon raft units are deployed along the outer perimeter of the cultivation zone as protective barrier rows, effectively dissipating strong current forces and preventing structural failures such as anchor stake dislodgement and line entanglement [29]. The principal drawback of this method, however, is its comparatively high cultivation cost relative to the other culture methods; furthermore, a larger cultivation area is generally required to achieve production efficiency comparable to that of the horizontal kelp rope culture method [29].

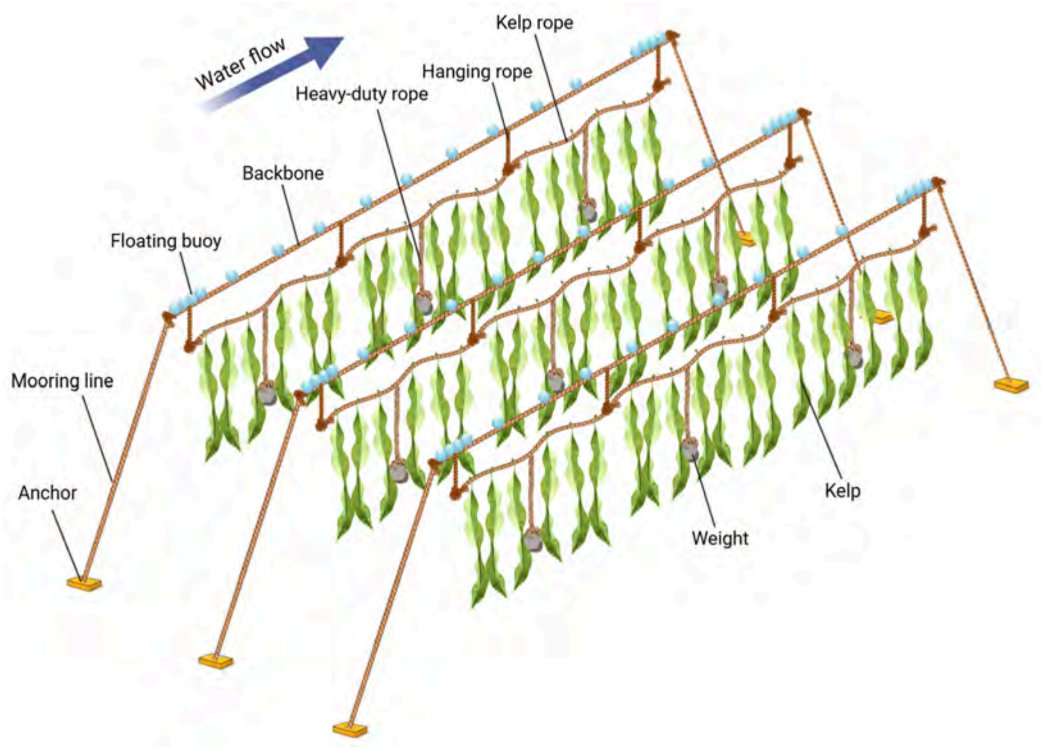

Figure 5. One-dragon kelp rope raft culture. Kelp ropes are connected in parallel to the backbone.

A comparative summary of the three single-line-based kelp cultivation methods is provided in Table 1. Each kelp cultivation method possesses distinct advantages, limitations, and environmental suitability. According to a dense-planting yield comparison experiment conducted by the Shandong Mariculture Research Institute in 1962 [29], which compared horizontal and vertical culture methods, kelp grown under the horizontal configuration exhibited a higher daily growth rate than that under the vertical configuration, producing larger individual sporophytes with an increase in individual dry weight of approximately 43–124 g [29]. In the comparative trial, the overall yield obtained from the horizontal method exceeded that of the vertical method by an average of 23.4% for kelp farms of equivalent area [29]. These results indicate that horizontal culture method yields significantly greater biomass than vertical culture method and is therefore the preferred approach for production intensification. The three cultivation methods can be selectively applied or transitioned between them according to local sea conditions and the developmental stage of the kelp. During the period immediately following transplantation of the kelp sporophytes, the juvenile plants are highly sensitive to light; the hanging kelp rope culture method may therefore be adopted, as most of the thalli suspended along the kelp ropes remain shaded, allowing the holdfasts of the sporophytes to form earlier and thereby promoting growth [29]. Once the kelp attains a length of approximately 2 m, however, self-shading among the plants reduces the available light intensity and impedes further growth; at this stage the kelp ropes can be repositioned horizontally, transitioning the system to the horizontal kelp rope raft culture method [29]. In more exposed, deeper offshore waters, the one-dragon kelp rope raft culture method should be considered [29]. Among the three cultivation methods, the one-dragon method is the most suitable for open-sea applications, owing to its superior resistance to wave action and its compatibility with mechanized operations.

Table 1. Comparison between three different kelp cultivation methods.

Comparison Aspect	Horizontal Kelp Rope Raft Culture	Vertical Kelp Rope Raft Culture	One-Dragon Kelp Rope Raft Culture
Cultivation orientation	Horizontal	Vertical	Aligned with prevailing current (serial layout)
Yield per unit area	High	Low	Moderate
Labor demand	Moderate	High	Low
Engineering complexity	Moderate	Low	High
Mechanization potential	Moderate	Low	High
Resistance to currents and waves	Moderate	Low	High
Offshore adaptability	Moderate	Limited	Strongest

The mooring lines used for these three methods are predominantly composed of polyethylene rope or polyethylene–red palm fiber blended rope with relatively low tensile strength. The anchoring systems rely on simple wooden stakes or stone sinkers for station keeping. The buoyancy elements consist of plastic or foam floats that provide only limited buoyancy. Collectively, these characteristics render conventional floating cultivation structures incapable of withstanding the high-intensity hydrodynamic forces characteristic of true offshore marine environments, where water depths typically reach 50 m or more [21–23]. A different cultivation infrastructure must be developed for offshore kelp farming.

The one-dragon configuration achieves its structural and mechanization advantages at the cost of areal productivity; that is, a larger sea area is required for output equivalent to the horizontal method [29]. The three methods therefore do not form a simple performance ranking, but a trade-off between yield density (favoring horizontal), labor intensity (disfavoring vertical) and hydrodynamic robustness with mechanization compatibility (favoring one-dragon).

2.2. Mechanization of Kelp Harvesting: Structural Constraints and Engineering Implications

In China, kelp harvesting has long relied primarily on manual operations. This harvesting method results in low harvesting efficiency and leads to high labor costs that account for a significant portion of total production expenses [24]. Consequently, numerous mechanized harvesting devices for kelp have been proposed and trialed [8]. Hong et al. [8] conducted an excellent review of 53 existing harvesting vessel designs in China, classifying them into three principal categories: lifting-type, chain-type, and traction-type. Typical examples of this three mechanical harvesting equipment are shown in Figures 6–8. Table 2 compares these three types of kelp harvesting devices.

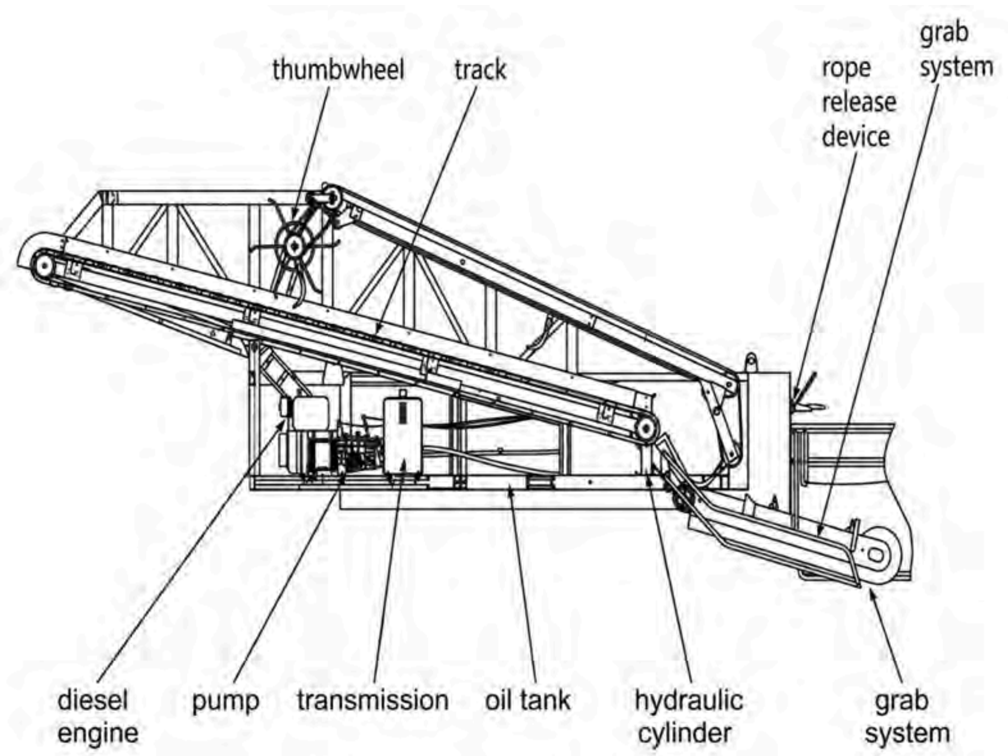

Figure 6. Kelp harvesting device (adapted from Chinese patent CN104303697A [30]).

The bow-mounted machine of Figure 6 [30] cuts the seedling line free and lifts it aboard; the chain-driven vessel of Figure 7 [31] takes the more unusual approach of using the cultivation structure itself as a track, gripping the mainline to propel itself along the raft and dispensing with manual cutting altogether; and the crane-and-claw device of Figure 8 [32] addresses not harvesting but the stage after it, where vessel motion causes kelp loss during transfer. Each takes the rope geometry as given; none modifies it, and the harvesting devices in Figures 6 and 7 have yet to be validated at sea [30,31].

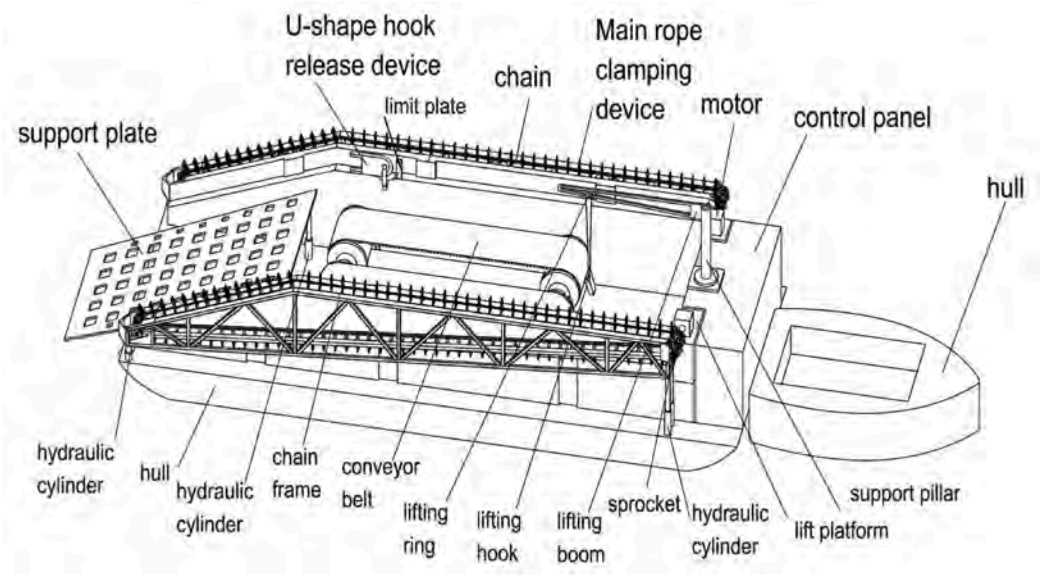

Figure 7. A chain-driven kelp harvesting ship (adapted from Chinese patent CN109699284B [31]).

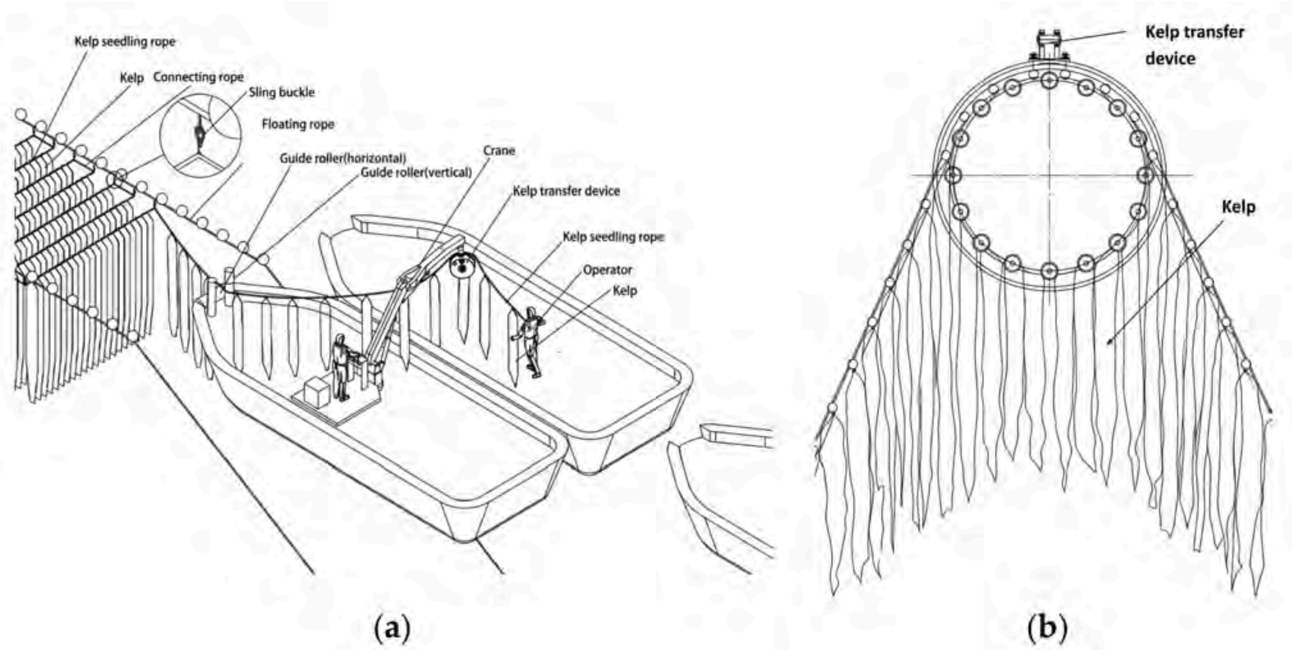

Figure 8. Structure of kelp harvest and transfer device, (**a**) Overall structure; (**b**) Details of kelp transfer device with claw structure [32,33].

What these three classes have in common is more instructive than what distinguishes them. In each case, the machine has been designed around a fixed rope geometry. Most notably, existing vessels exhibit poor seakeeping performance under moderate-to-severe wave conditions and hull dimensions that are incompatible with the dense spatial configuration of nearshore raft structures. Furthermore, harvesting operations frequently result in significant kelp detachment during onboard transfer, while mechanical interactions between the vessel and raft components cause recurring structural damage to mooring ropes and floats. Collectively, these limitations prevent current machines from achieving the twin objectives of meaningful labor reduction and efficient large-scale harvesting. Consequently, most kelp harvesting devices developed in China to date remain confined to prototype validation and have yet to attain commercial-scale deployment [8,24].

Table 2. Comparison between different kelp harvesting machines.

Machine Class	Working Principle	Structural Interface with Raft	Reported Failure/Limitation Mode	Refs.
Lifting-type	Cutters sever lifting ropes at both ends of seedling line; hooks + guide belt draw kelp aboard	Requires access along a single mainline; hull must pass between mainlines	Kelp detachment during onboard transfer; poor seakeeping in moderate–severe seas	[8,30]
Chain-type	Symmetric chain frames clamp the mainline and propel the vessel along it	Loads the mainline directly; depends on mainline tension and diameter consistency	Mainline damage; sensitivity to non-standard rope specification	[8,31]
Traction-type/claw transfer	Crane + claw transfers harvested kelp to a transport vessel	Operates adjacent to, not within, the raft grid	Requires a second vessel; mechanical interaction with mooring ropes and floats	[8,32,33]

From a structural engineering perspective, the barrier to mechanized harvesting lies not in the equipment but in the cultivation structure itself. China's single-line-based system [7,24,25] imposes three constraints that no machine operating within it can overcome. The first is load: a fully grown seedling rope carries some 80 plants of approximately 1.25 kg, so that roughly 100 kg (or 1 kN) must be lifted per rope [23,32]. Furthermore, the lifting process must overcome wave-induced hull motion and remain synchronized with the vessel [8].

The second is geometric confinement: mainlines are spaced only 5–8 m apart [7] and interconnected by hanging and seedling ropes into a dense tensioned network. So, hull beam is bound above yet must still accommodate harvesting machinery. Current vessel designs have not resolved the problem [24,34]. Neither dimension was designed to accommodate mechanized harvesting. Traditionally, harvesting is carried out manually by two workers in a small boat positioned between the mainlines [28]. Accordingly, the 5–8 m spacing between the mainlines appears to have been established primarily to facilitate this manual harvesting operation, suggesting that the raft configuration was designed around human access and handling from the outset [26].

The third constraint is the absence of dimensional standards. Key structural parameters remain experience-based and locally adapted, varying between regions, between farms and even between operators within the same region [8], and so the boundary conditions are undefined. Unlike terrestrial mechanized agriculture, which is predicated on standardized crop geometry and row spacing [35], kelp cultivation offers no fixed dimensions to design against. What is required is not a further generation of harvesting prototypes but mechanization-compatible structural standards specifying geometric parameters together with minimum load-bearing capacities, allowable deformation limits and material fatigue properties. Weak enforcement, retrofitting cost, dispersed ownership and equipment compatibility compound the problem and are treated separately in Table 3.

Responsibility for such standards would most plausibly rest with the Ministry of Agriculture and Rural Affairs, which already issues agricultural industry standards for aquaculture machinery [4], working jointly with the classification and marine-structures community, since the load bearing and fatigue provisions fall outside conventional fisheries standardization expertise.

Table 3. Different types of barriers and the needed actions.

Barrier	Nature	Action
Absence of standards	No specification of frame dimensions, float spacing, rope length. No specification of rope material or load capacity.	Structural standards covering geometry, load capacity, allowable deformation, material fatigue.
Weak Enforcement mechanisms	Outside mandatory scope of existing standards. Household-contract operation; local-authority enforcement.	Compliance tied to sea-area use licensing (issue and renewal).
Retrofit cost	Upgrade cost borne by farmers Short-term returns uncertain.	Phased: mandatory for new/offshore sites, subsidy for existing sites.
Fragmented ownership	Small farm scale; geometry set farm by farm. No block-level planning authority.	Planning at zone scale rather than individual owner scale.
Equipment interface compatibility	Vessel beam limited by 5–8 m mainline spacing. Structure-only standards omit equipment interface.	Defined vessel passage envelope; structural and equipment standards to be matched.

3. Structural Implications of Kelp-Based IMTA

Integrated multi-trophic aquaculture (IMTA) co-locates species from different trophic levels so that the waste of one becomes a resource for another. For example, fed species release dissolved nutrients and particulate organics, suspension-feeding shellfish remove the particulates, seaweeds assimilate dissolved nitrogen and phosphorus, and deposit feeders such as sea cucumbers consume material reaching the seabed [9–14]. China is the principal exception in scale driven by regulatory pressure on mariculture effluent following the 2015 Water Pollution Prevention and Control Action Plan [36] and by domestic demand for shellfish and seaweed [17,37]. Chinese IMTA reached approximately 40% of national marine aquaculture output by 2022 [17], with kelp participating in most configurations implemented [38]. Their ecological mechanisms and economic performance are reviewed comprehensively elsewhere [9–17] and will not be revisited here.

IMTA is therefore treated here not from an ecological strategy standpoint but as a structural modification of the kelp longlines. Sanggou Bay (37°02′ N, 122°34′ E, see Figure 1c) serves as the reference case. It hosts the largest and longest-established bay-scale IMTA system in China, with scallop–kelp polyculture documented since the early 1990s [15,39–41]. So, its configuration reflects three decades of iterative adaptation rather than a single trial design, and it is the setting in which kelp is the principal extractive crop rather than a secondary one. Two of the configurations practiced there are examined in the sequel [38]: the shellfish–kelp system, and the abalone–kelp–sea cucumber system. For both, the structural parameters reported below have been derived from a single practice guide [42], that unfortunately does not state any design basis, sample population or applicable sea state.

3.1. Shellfish–Kelp IMTA System in Sanggou Bay

The ecological complementarity of the scallop–kelp pairing is well documented and is the reason the configuration has persisted. Bivalves regenerate dissolved inorganic nitrogen that is advected to adjacent kelp, so that kelp grown in polyculture does not exhibit the late-season yellowing and tip rot observed in monoculture under nitrogen limitation. While kelp uptake moderates the eutrophication risk associated with dense bivalve stocking; the relative density of each species is also lower than in monoculture, mitigating the slow growth and elevated mortality associated with overstocking [42–47]. These mechanisms are treated comprehensively in ecological literature and are not developed further here. Our concern is what the arrangement affects the structural form.

Structurally, the system is a single-line raft with horizontal method (Figure 9). The headline, which carries the buoys and floats, is deployed in sections of approximately 100 m with about 5 m between sections and is typically aligned with the prevailing current. Mooring lines of 2.4 cm diameter are attached at both ends, with a length of approximately three times the water depth and are fixed to the seabed by anchors or piles. Buoys are distributed along the headline at regular intervals to provide flotation. Lantern nets containing the bivalves are suspended from the headline at a spacing of approximately 2.3 m (some 43 nets per 100 m section) while kelp culture ropes, each carrying about 40 seedlings, are suspended horizontally between adjacent headlines [42].

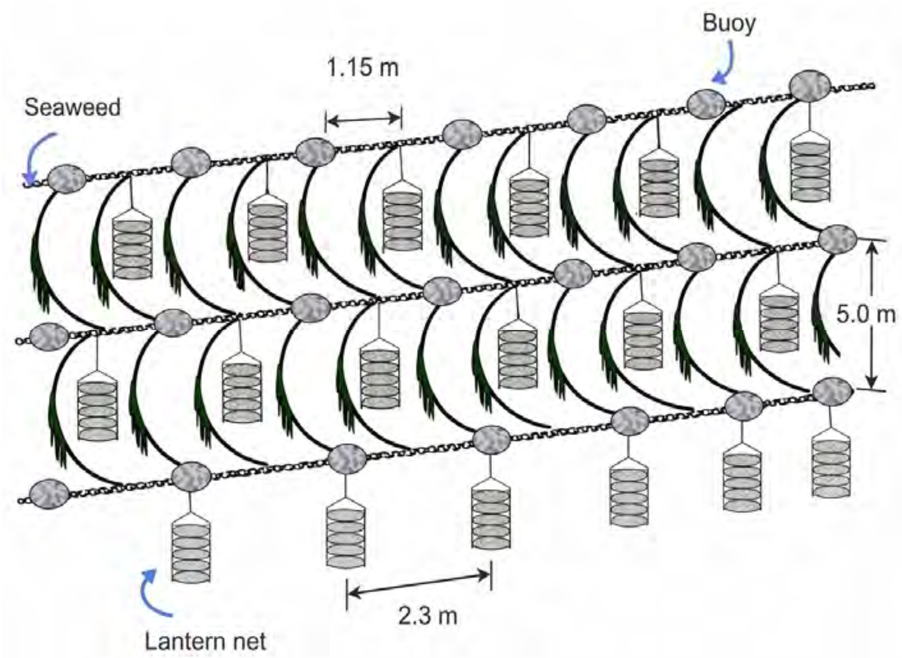

Figure 9. Structure for shellfish–kelp polyculture system [42].

Compared with the monoculture horizontal raft of Section 2.1, the headline length, mooring length ratio and anchoring method are essentially unchanged; what has changed is the load the headline carries. The suspended bivalve biomass, the submerged mass and projected area of the lantern nets themselves, and the resulting increase in static tension and hydrodynamic drag are not quantified in the source, nor is any increase in float provision or mooring capacity specified. The 2.4 cm mooring line diameter is the only component dimension reported, and no material grade or breaking load accompanies it.

3.2. Shellfish–Kelp–Sea Cucumber IMTA System in Sanggou Bay

The three-species configuration is driven principally by abalone economics. Abalone are fed fresh or formulated macroalgal feed, and the fraction not consumed degrades water quality and depresses farm productivity. In the integrated arrangement, kelp serves simultaneously as feed and as a sink for dissolved abalone waste, while sea cucumbers, as detritivores that consume the particulate fraction and act as cleaners within the cages [42]. A seven-month field trial near Lidao recorded a doubling of mean sea cucumber wet weight, confirming the practicality of co-culture within the same cages and noting that the method requires little additional labor or investment relative to tank, pond or benthic sea cucumber culture [44]. Both sea cucumber and abalone command high market value in China, which is why the configuration has spread.

The structure for the three-species configuration is the horizontal kelp rope raft culture method of Section 2.1, reconfigured around the abalone cages (Figure 10). A farming unit comprises four culture lines with 5 m spacing between them; each headline is 80–100 m long and supports thirty cages suspended vertically at 2.5 m vertical spacing. Each cage is approximately 0.5 m in diameter and 0.6 m deep, is divided into three layers, and holds about 280 abalone of 3.5–4.0 cm shell length together with two to three sea cucumbers per layer at an initial weight of 60–80 g. The kelp component is carried on ropes formed from two 2.5 m lengths joined end to end and suspended horizontally between adjacent headlines, each rope carrying about 70 seedlings, with 2–3 m between ropes [42].

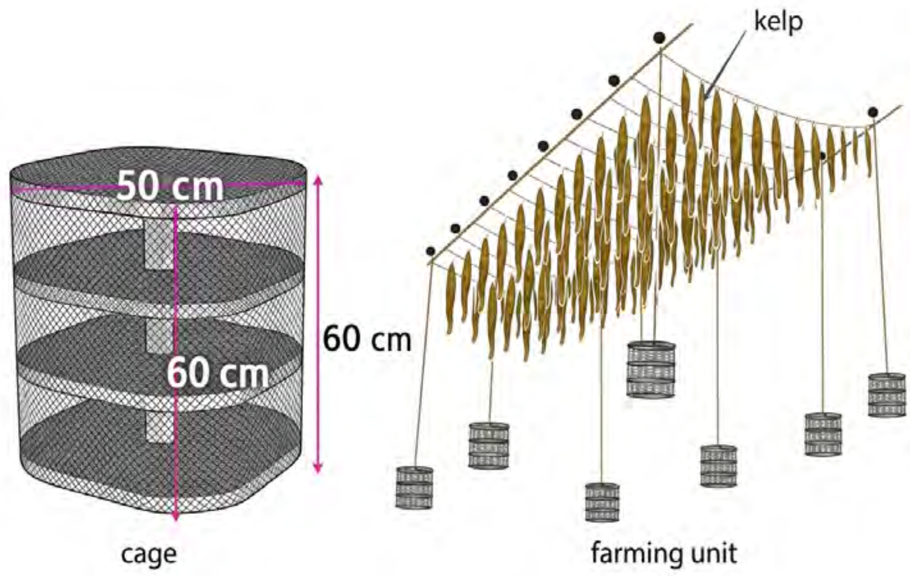

Figure 10. Structure of abalone–kelp–sea cucumber longline IMTA system [42].

This configuration departs substantially from the monoculture longline. Considering the reported cage dimensions, the thirty cages require 9 m^2 of additional projected area per headline. This is merely a preliminary estimate, as it does not account for the permeability of the cages, the shading effect between adjacent cages, or the influence of the kelp canopy itself. However, it highlights the significant difference in scale when compared to structures consisting solely of suspended cultivation lines.

3.3. Structural Implications and the Offshore Question

Two features of Table 4 stand out. The first is that co-culture increases the loading carried by the kelp longline without any reported change to the structure carrying it: in both systems the headline length, mooring length ratio and anchoring method are those of the monoculture raft, while the suspended payload is substantially greater. The second is the pattern of blank cells, no mooring tension, headline sag, float provision or dynamic response measurement reported for either configuration, with no design sea state reported for any of the three. This is not for want of an applicable method. The hydrodynamic loading of suspended culture units on longlines has been characterized extensively for mussel farms, through drag and inertia coefficients for dropper lines [48,49], coupled numerical models of complete systems [50], and comparative loading analyses of configurations in wave-exposed commercial conditions [51]. What is absent is the application of these methods to kelp-based IMTA, in China or elsewhere.

Table 4. Structural attributes of kelp monoculture and the two Sanggou Bay IMTA configurations.

Structural Attribute	Kelp Monoculture (Horizontal Raft)	Shellfish–Kelp	Abalone–Kelp–Sea Cucumber
Headline/backbone length	60–100 m [25]	~100 m per section, ~5 m between sections [42]	80–100 m; 4 culture lines per unit, 5 m spacing [42]
Mooring line	2–3 × water depth; polyethylene, 15–30 mm [25]	2.4 cm diameter, ~3 × water depth [42]	Same as shellfish–kelp system [42]
Anchoring	Wooden stakes, or 3–6 t anchors [25]	Anchors or piles [42]	Same as shellfish–kelp system [42]
Kelp rope arrangement	Transverse between backbones; hanging depth $\leq$ 3 m [25]	Horizontal between adjacent headlines; ~40 seedlings per rope [42]	Two 2.5 m ropes joined; ~70 seedlings per rope; 2–3 m between ropes [42]
Suspended co-culture units	None	Lantern nets at ~2.3 m spacing (~43 per 100 m) [42]	3-layer cages, 0.5 m dia. × 0.6 m, 30 per headline, 2.5 m vertical spacing [42]
Stocking in suspended units	None	Scallops or oysters [42]	~280 abalone (3.5–4.0 cm shell length) per cage; 2–3 sea cucumbers (60–80 g) per layer [42]
Reported buoyancy provision	Plastic, glass or foam floats; selection described as arbitrary [25]	Buoys (30 cm diameters) at regular intervals along headline [42]	Same as shellfish–kelp system [42]

This absence bears directly on the offshore transition. Buck et al. [52] report that only one site worldwide operates IMTA at commercial scale under genuinely offshore conditions—the Zhangzidao ranch in the northern Yellow Sea, where Yezo scallop (Patinopecten yessoensis) is bottom-sown and macroalgae arise as an incidental by-product rather than a cultivated crop [53,54]. Zhangzidao is incidental rather than engineered IMTA, and the structural antithesis of the Sanggou Bay systems: carrying no headline, mooring, buoyancy system or suspended payload, it is subject to none of the hydrodynamic loading that governs longline survivability. The one commercially proven route to offshore IMTA is thus the one that dispenses with the floating structure altogether. However, that route is closed to kelp, which must be held within the photic zone. Suspended kelp-based IMTA consequently has no offshore commercial precedent anywhere in the world.

4. Exploration into Deep and Offshore Seaweed Farming

As seaweed production continues to increase each year, several problems have begun to appear [18]. Nearshore environmental capacity is being exceeded: coastal space is limited, and high-density shellfish and seaweed culture raises disease risk [25], while ecological restoration, port and shipping infrastructure and marine conservation compete for the same waters traditionally used for floating rafts [55]. The market simultaneously demands larger-scale, more stable production and higher-quality products, for which offshore waters offer better water quality, lower pollution and far more space [18,56]. Government policy has reinforced both, strongly supporting the relocation of marine farming from nearshore zones to deep and open-ocean areas [57,58].

Chinese practice distinguishes these zones geographically: nearshore farming within bays or within sight of the coast (about 2 km); offshore farming beyond visual range but in less than 20 m of water; and open-ocean farming with water depth greater than 20 m [25,59]. From a structural standpoint these definitions are of limited use, since distance from shore and water depth do not by themselves specify a design condition. What the relocation entails is not spatial expansion but a transformation of the engineering load environment: moving from sheltered bays to open water substantially increases wave action, current speed and wind loading, and therefore requires the design basis of the cultivation structure to be reassessed rather than simply transplanted.

4.1. Current Offshore Seaweed Cultivation Experiences in China

Offshore seaweed cultivation in China is concentrated in Fujian and Shandong; the principal installations are summarized in Table 5. Fujian has moved seaward into a demonstration zone outside Huangqi Bay, the artificial seaweed fields of Huangwanyu, the Dinghai Bay platform cluster, where artificial seaweed fields are combined with fish and shellfish cages in what is effectively a deep-water IMTA system of the kind discussed in Section 3. An open-water zone off Luoyuan Bay (see Figure 1d) was opened as nearshore capacity there approached saturation [55,60–63]. In Shandong, "deep-sea small kelp" is farmed 8–10 nautical miles offshore at depths of 30–40 m near Rongcheng and Weihai (see Figure 1c for their locations), supported by dedicated processing and branding infrastructure [64]. Breeding programmes in both provinces have produced varieties intended for deep water: the "Huangguan" series and "borderless kelp" at the national kelp breeding base in Lianjiang [65], and Hokkaido–Rongcheng hybrids at Rongcheng [66]. Interest in the Shandong sites sharpened after the mass mortality of nearshore kelp there in 2021–2022, an event attributed to an extreme rainfall episode far inland, transmitted to the coast as an anomalous freshwater and nutrient flux [67]. That was an environmental rather than a structural failure: it illustrates the exposure of nearshore sites to land-derived shocks, not any mechanical advantage of deeper water.

Table 5. Chinese offshore seaweed cultivation projects assessed against design load environment, structural response and verification.

Project	Location	Design Environment	Structural Concept	Change Relative to Nearshore Practice
Lianjiang demonstration zone, outside Huangqi Bay [61,63]	Lianjiang, Fujian	~3 km from shore; 94 ha; 5 m to 20 m water depth; 0.6 m wave height; 0.3 to 0.8 m/s current speed	Floating raft (nearshore single-line type) 1533 rafts	Component substitution only: expanded-foam buoys replaced by plastic buoys
Huangwanyu artificial seaweed field, Dajian Village [60]	Lianjiang, Fujian	94.3 ha; 5 m to 20 m water depth	Surface seaweed rafts combined with seabed artificial reefs and cage aquaculture	Addition of seabed reefs; vertical layering of the site
Dinghai Bay platform cluster [55]	Lianjiang, Fujian	88 ha; 17 m water depth	25 deep-sea platforms and 6005 deep-water cages; integrated fish cage, shellfish cage and artificial seaweed field	Purpose-built platforms for fish and shellfish; the seaweed component remains raft-based
Luoyuan Bay open-sea zone, Biling Township [62]	Luoyuan, Fujian	90.5 ha; 17.5 m to 41 m water depth; 0.69 m/s current speed	Raft-based longline for *Gracilaria lemaneiformis*, aligned with prevailing current	Longline orientation to current; eco-friendly buoys
Haizhibao "deep-sea small kelp" farm, Jiaodong Bay [66]	Rongcheng, Shandong	8–10 n miles offshore; 30–40 m water depth	Floating raft (nearshore single-line type)	Biological: Hokkaido and Rongcheng hybrid varieties adapted to deep water
Weihai "deep-sea small kelp" area [64]	Weihai, Shandong	~8 n miles offshore; 40 m water depth; Strong current, 0–5 °C	Floating raft (nearshore single-line type)	Siting only

4.2. Offshore Seaweed Cultivation Structure in the World

The programmes summarized in Table 6 answer the same three questions differently. Spanning four decades and six countries, each began not from an existing nearshore raft but from the intention to operate in open water, and each therefore returned a verifiable outcome. Those outcomes cluster into three failure mechanisms rather than eight unrelated histories: buoyancy-element integrity, which sank the Netherlands H-frame in January 2013 and contributed to the loss of the 1970s quarter-acre module [18,20]; station-keeping under extreme events, that is, the residual uncertainty that the Maine lattice system identified in anchor placement accuracy and tension control even after surviving a full year of operation including harvest [19]; and the biological–structural interface, the same trial having found the holdfast attachment of Saccharina latissimi to fiberglass rods to be weak [19], a failure mode with no counterpart in conventional marine structures and not reported in the Chinese literature. Across four decades these structures have failed at their components, and not at their global configuration. A recent development in offshore seaweed cultivation is the Climate Foundation/University of Queensland's submersible platform that has deep cycling capability to reach 100 m water depth and beyond off Cebu Island, the Philippines [22]. So far, all these offshore seaweed cultivation infrastructures have not been commercialized due to engineering challenges that have yet to be resolved.

Table 6. International offshore seaweed cultivation structures assessed against the same criteria.

Project	Location	Design Environment	Structural Concept	Change Relative to Nearshore Practice	Verification and Outcome	Reported Failure or Limiting Mechanism
Quarter-acre module, Marine Biomass Program (General Electric), 1970s [20]	Newport Bay, USA	0.1 ha; 3 m wave height, strong current, suspended 12–15 m below water surface	Inverted umbrella with large buoys, central pumping pipe for deep-water upwelling	Designed for open ocean	Programme discontinued	Harsh marine environment combined with inadequate structural design
Seaweed–wind integrated ring, 2000 [68,69]	North Sea, Spain	Less than 50 m water depth, 3 m wave height	Circular cultivation structure integrated with a wind turbine	Designed for multi-use	Joint trial; not adopted commercially	Limited deployment and harvest weather windows
H-frame with SPAR buoys, 2011 [18,70]	North Sea, Netherlands	8 m wave height, 22 m water depth	H-frame supported by SPAR buoys	Designed for exposed water	Tested from 2011; sank January 2013	Structural instability and flooding of the H-frame pipe
Seaweed Carrier, 2009 [18]	Trondheim-Froya area, Norway	Open ocean	Sheet-like structure with cables and single moorings	Designed to facilitate commercial-scale kelp cultivation and to withstand rough water	Not in commercial use	No failure
Tension-Leg Platform, 2016 [18]	Cheongsan Island, South Korea	35 m water depth	Grid system with long lines	Designed for high density deployment of cultivation systems	Not in commercial use	High cost of installation

Table 6. *Cont.*

Project	Location	Design Environment	Structural Concept	Change Relative to Nearshore Practice	Verification and Outcome	Reported Failure or Limiting Mechanism
Macroalgal Cultivation Rig, 2010–2019 [71]	Faroe Islands	4 m wave height, 70 m water depth	Long line system	Designed for offshore area	In operation now	No failure
Lattice-type line system, University of New Hampshire, 2024 [19]	Saco Bay, USA	13 m water depth, 1.25 n miles from shore	Lattice seaweed line system with multi-shaft helical anchors and fiberglass rods	Anchoring system developed specifically for the site	One year of operation including growth and harvest	Weak holdfast attachment of *Saccharina latissima* to fiberglass rods
SubTractors submersible platform, Climate Foundation Australia/University of Queensland, 2025 [22]	Cebu, Philippines	Deep cycling to >100 m, wave height up to 4 m; current speed 0.6 m/s	Submersible platform with movable buoys that traverse the mooring lines	Designed for deep cycling to reach cold nutrient-rich water and active avoidance of strong waves in extreme sea states	Trailed offshore; development underway to expand to one hectare	Under development

4.3. Technical Bottlenecks and Research Gaps in Offshore Seaweed Cultivation in China

The three bottlenecks set out below are not a general catalogue of offshore engineering difficulties. Each is identified by a specific gap visible in Tables 5 and 6, and each is stated here in the form in which it applies to Chinese kelp cultivation structures.

4.3.1. Anchoring and Positioning Systems

This bottleneck is exposed by the station-keeping column of both tables. Mooring-line length and layout directly control both system cost and safety, while conventional shallow-water fixed methods used in China are difficult to apply in deep water and are prone to instability or drift under extreme wind and wave events [72]. Field investigations by [39] indicate that when offshore current velocities exceed 0.9 ms^{-1}, strong-wind conditions can lead to risks such as anchor pull-out and raft entanglement. Safety must therefore be enhanced through reinforced anchors, thicker mooring and float lines, and the deployment of cross-current single-line systems in parallel connection arrays along the outer perimeter [25]. Recent research on the dynamic responses of mooring systems employing high-modulus polyethylene (HMPE) ropes in offshore seaweed farm configurations under combined wave–current loading has demonstrated that mooring line tension may exhibit significant nonlinear amplification under extreme sea states, imposing stringent requirements on the selection of mooring components and the fatigue design thereof [73].

4.3.2. Structural Dynamic Response

This bottleneck follows directly from the blank design-environment and verification columns of Table 5. The intensified wave and current loading characteristics of offshore environments significantly excites the dynamic response of floating raft structures, inducing larger overall displacements, greater fluctuations in rope tension, and more pronounced vibration of local structural components [74]. Traditional bamboo rafts or lightweight floating rafts lack systematic ultimate-capacity definitions and fatigue verification, resulting in insufficient wave resistance and poor long-term reliability [72]. In the existing literature on shallow-water kelp cultivation [5,7,24,25,29], the raft-based kelp aquaculture structures described are largely devoid of any reported data on rope tension or component displacement. At present, most offshore kelp cultivation in China relies on minor reinforcement and outward relocation of existing raft systems, rather than purpose-designed modular units for deep-water conditions [25,74]. However, experimental data from recent studies on offshore kelp structures indicate that water depths in offshore areas far exceed 20 m, with wave heights reaching up to 4 m and current velocities as high as 0.9 m/s; under excessively high current velocities, floating raft systems are susceptible to anchor detachment and the risk of the entire raft becoming entangled [21–23,39]. At present, China has virtually no seaweed farms operating at depths exceeding 50 m, forcing designers to rely on numerical simulations to estimate hydrodynamic tolerance at different depths [75]. Furthermore, when harvest vessels interact dynamically with flexible floating raft structures under wave conditions, the resulting coupled interaction constitutes a complex engineering problem that remains insufficiently addressed in the literature—one that has decisive implications for the feasibility of mechanized offshore harvesting.

4.3.3. Structural Fatigue and Full Life Cycle

Neither table records a fatigue verification for any system, Chinese or international. Marine environmental loads are characterized by their persistent, stochastic, and long-term cumulative nature, posing severe challenges to the fatigue performance of aquaculture structures [76]. Bamboo members, conventional polyethylene ropes, and plastic floats employed in traditional nearshore floating rafts [25] were generally selected based on availability and cost rather than systematic structural and fatigue verification. Their service lives can vary substantially with material quality, UV exposure, marine biological degradation, abrasion, environmental loading and maintenance. Field reports indicate typical service lives of approximately 1–4 years for bamboo members and 5–8 years for conventional polyethylene ropes, while the durability of plastic floats varies widely with polymer type, UV stabilisation and manufacturing quality. Consequently, quantitative failure and fatigue data for these components under representative seaweed-farming loading conditions remain limited.

From a structural engineering perspective, the design of offshore aquaculture facilities should be systematically verified against three limit states: ultimate limit state (ULS), fatigue limit state (FLS), and accidental limit state (ALS) [75,77]. However, full life-cycle reliability assessment of offshore aquaculture facilities in China remains largely absent [78]. Current offshore aquaculture systems still depend heavily on manual inspection and operation [72], with limited automation, mechanization, and remote operation and maintenance capability. For seaweed farming, this is reflected in labor-intensive deployment and retrieval of rafts, manual mooring maintenance, insufficient equipment for harvesting, transport, and dewatering pretreatment in deep water, and incomplete real-time monitoring systems (e.g., current speed, wave height, temperature, and blade length) [79].

5. Concluding Remarks

This paper presents an up-to-date review of kelp cultivation structures in China from a structural engineering perspective, organized around three interconnected aspects: nearshore single-line-based cultivation structures and the associated mechanization challenges, the practice of Integrated Multi-Trophic Aquaculture (IMTA) systems in China, and the trends and engineering bottlenecks characterizing the transition of seaweed cultivation toward offshore deepwater environments.

Traditional nearshore kelp cultivation in China is predominantly based on the single-line system. Depending on how the kelp ropes are connected to the backbone, three cultivation methods are distinguished: horizontal, vertical, and one-dragon kelp rope raft culture. The horizontal method yields higher biomass than the vertical method, while the one-dragon method demonstrates the greatest potential for offshore adaptation, owing to its superior wave resistance and alignment with the prevailing current. The fundamental barrier to mechanized harvesting lies not in the harvesting equipment but in the structural characteristics of cultivation systems designed from the outset for manual operation.

China's IMTA systems, exemplified by the large-scale shellfish–kelp–sea cucumber polyculture in Sanggou Bay, are among the most mature and ecologically effective integrated aquaculture models in the world, with clear benefits in nutrient cycling, eutrophication mitigation and species productivity. Their structural configurations, however, are predominantly nearshore longline arrangements that have not been systematically adapted for offshore deepwater conditions. This is a gap that grows more apparent as the industry expands beyond sheltered embayment.

Recent offshore pilot projects in Fujian and Shandong represent meaningful industrial progress in relocating kelp cultivation toward deeper, more exposed waters. From a structural engineering perspective, however, the structures employed remain incremental seaward extensions of existing nearshore floating rafts rather than systems purpose-designed for offshore conditions. That transition entails a fundamental transformation of the engineering load environment, with substantially increased wave action, current velocity and wind loading. Three critical engineering bottlenecks have been identified: the complexity of mooring and station-keeping under extreme hydrodynamic loading; the inadequate characterization of structural dynamic response under combined wave and current action; and the absence of systematic fatigue verification and full life-cycle reliability assessment.

In contrast to China's dominance in production scale, non-traditional seaweed-producing regions (such as the United States, Europe and Australia) have initiated dedicated development of purpose-designed offshore cultivation structures, including submersible platforms with deep-cycling capability, lattice-type line systems with helical anchors, and tension-leg platform concepts. Although these initiatives remain largely pre-commercial, they represent a fundamentally different engineering paradigm: structural systems designed from the outset for energetic offshore conditions rather than incrementally adapted from nearshore prototypes. China, despite its unparalleled aquaculture experience and production scale, exhibits a notable gap in offshore structural engineering innovation.

Ultimately, the transition of China's kelp industry offshore should be understood not as a geographic extension of nearshore practice but as a fundamental engineering challenge demanding purpose-designed structural solution. This is the defining challenge and the strategic opportunity for the next stage of the country's seaweed aquaculture industry.

Literature Search Strategy and Selection Criteria

For this review work, we have sourced information from the Web of Science Core Collection, Scopus and Google Scholar, and Chinese-language sources in CNKI, Wanfang and VIP, using combinations of the terms [Saccharina japonica, kelp, seaweed aquaculture, raft/longline culture, offshore aquaculture, mooring system, China] and their Chinese equivalents [kelp, raft cultivation, mooring line, anchor, offshore cultivation and equipment]. Chinese patents were retrieved from the CNIPA patent database (and cross-checked in Espacenet), because engineering details of farming structures (such as raft geometry, buoyancy and mooring configurations) are frequently disclosed only in patent documents and rarely reported in the peer-reviewed literature; patents were therefore used to document design concepts, not as evidence of field performance. Grey literature, including national and industry standards (GB, SC/T), provincial technical specifications, and fishery statistics (China Fishery Statistical Yearbook), was included for the same reason, and quantitative information drawn from such sources was cross-checked against peer-reviewed publications or official statistics wherever possible. The search covered the period 1950–2025; publications before 2000 were used mainly to trace the historical development of kelp cultivation in China, whereas the analysis of nearshore-to-offshore transition draws primarily on sources published between 2010 and 2025. Studies were included if they addressed the structure, configuration or engineering of kelp farming systems in Chinese waters (or provided directly comparable international experience), and were excluded if they dealt solely with physiology, breeding or post-harvest processing without reference to farming structures, or if full texts could not be obtained.

Author Contributions: Writing—original draft preparation, C.H. and W.L.W.; writing—review and editing, C.M.W. and H.P.N.; supervision, C.M.W.; project administration, C.H.; funding acquisition, C.M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Australian Government's Cooperative Research Centre Program, grant number CRCXX000001 (previously 20180101).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. White, W.L.; Wilson, P. World Seaweed Utilization. In *Seaweed Sustainability: Food and Non-Food Applications*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 7–25.
2. Lindsey Zemke-White, W.; Ohno, M. World Seaweed Utilisation: An End-of-Century Summary. *J. Appl. Phycol.* **1999**, *11*, 369–376. [CrossRef]
3. FAO. Global Aquaculture Production. In *Fisheries and Aquaculture*; FAO: Rome, Italy, 2026. Available online: http://www.fao.org/fishery/collection/aquaculture/en (accessed on 17 August 2026).
4. The Bureau of Fisheries of China's Ministry of Agriculture and Rural Affairs; the China Society of Fisheries. *China Fishery Statistical Yearbook 2025*; China Agriculture Press: Beijing, China, 2025.
5. Hu, Z.M.; Shan, T.F.; Zhang, J.; Zhang, Q.S.; Critchley, A.T.; Choi, H.G.; Yotsukura, N.; Liu, F.L.; Duan, D.L. Kelp Aquaculture in China: A Retrospective and Future Prospects. *Rev. Aquac.* **2021**, *13*, 1324–1351. [CrossRef]
6. Zheng, Y.; Jin, R.; Zhang, X.; Wang, Q.; Wu, J. The Considerable Environmental Benefits of Seaweed Aquaculture in China. *Stoch. Environ. Res. Risk Assess.* **2019**, *33*, 1203–1221. [CrossRef]
7. Liu, F.; Niu, J.; Sui, Z.; Shan, T.; Wang, T.; Tang, X.; Liang, Z.; Pang, S. Overview and prospects of China economic seaweed cultivation technology. *J. Agric. Sci. Technol.* **2020**, *22*, 1–9. [CrossRef]
8. Hong, Y.; Lu, L.; Zhang, Z.; Zhu, Y.; Yang, M.; Jiang, T.; Chen, Z. Development Status and Trend Analysis of Kelp Harvesting Devices in China. *J. Mar. Sci. Eng.* **2026**, *14*, 381. [CrossRef]
9. Troell, M.; Joyce, A.; Chopin, T.; Neori, A.; Buschmann, A.H.; Fang, J.G. Ecological Engineering in Aquaculture—Potential for Integrated Multi-Trophic Aquaculture (IMTA) in Marine Offshore Systems. *Aquaculture* **2009**, *297*, 1–9. [CrossRef]
10. Chopin, T.; Cooper, J.A.; Reid, G.; Cross, S.; Moore, C. Open-Water Integrated Multi-Trophic Aquaculture: Environmental Biomitigation and Economic Diversification of Fed Aquaculture by Extractive Aquaculture. *Rev. Aquac.* **2012**, *4*, 209–220. [CrossRef]
11. Chopin, T.; Yarish, C.; Wilkes, R.; Belyea, E.; Lu, S.; Mathieson, A.-T. Developing Porphyra/Salmon Integrated Aquaculture for Bioremediation and Diversification of the Aquaculture Industry. *J. Appl. Phycol.* **1999**, *11*, 463–472. [CrossRef]
12. Neori, A.; Chopin, T.; Troell, M.; Buschmann, A.H.; Kraemer, G.P.; Halling, C.; Shpigel, M.; Yarish, C. Integrated Aquaculture: Rationale, Evolution and State of the Art Emphasizing Seaweed Biofiltration in Modern Mariculture. *Aquaculture* **2004**, *231*, 361–391. [CrossRef]
13. Chopin, T. Marine Aquaculture in Canada: Well-Established Monocultures of Finfish and Shellfish and an Emerging Integrated Multi-Trophic Aquaculture (IMTA) Approach Including Seaweeds, Other Invertebrates, and Microbial Communities. *Fisheries* **2008**, *40*, 28–31. [CrossRef]
14. Kim, J.K.; Yarish, C.; Hwang, E.K.; Park, M.; Kim, Y. Seaweed Aquaculture: Cultivation Technologies, Challenges and Its Ecosystem Services. *Algae* **2017**, *32*, 1–13. [CrossRef]
15. Wartenberg, R.; Feng, L.; Wu, J.J.; Mak, Y.L.; Chan, L.L.; Telfer, T.C.; Lam, P.K.S. The Impacts of Suspended Mariculture on Coastal Zones in China and the Scope for Integrated Multi-Trophic Aquaculture. *Ecosyst. Health Sustain.* **2017**, *3*, 1340268. [CrossRef]
16. Edwards, P. Aquaculture Environment Interactions: Past, Present and Likely Future Trends. *Aquaculture* **2015**, *447*, 2–14. [CrossRef]
17. FAO. *Integrated Multitrophic Aquaculture: Lessons from China*; FAO: Bangkok, Thailand, 2022.

18. Bak, U.G.; Gregersen, Ó.; Infante, J. Technical Challenges for Offshore Cultivation of Kelp Species: Lessons Learned and Future Directions. *Bot. Mar.* **2020**, *63*, 341–353. [CrossRef]
19. Moscicki, Z.; Swift, M.R.; Dewhurst, T.; MacNicoll, M.; Chambers, M.; Tsukrov, I.; Fredriksson, D.W.; Lynn, P.; Landon, M.E.; Zotter, B.; et al. Design, Deployment, and Operation of an Experimental Offshore Seaweed Cultivation Structure. *Aquac. Eng.* **2024**, *105*, 102413. [CrossRef]
20. Tompkins, A.N. *Marine Biomass Program Annual Report for 1979*; Gas Research Institute: Chicago, IL, USA, 1980.
21. Nguyen, H.P.; Wang, C.M.; von Herzen, B.; Huang, C. Hydroelastic Responses of a Submersible Ring Structure for Offshore Seaweed Cultivation under Wave Action. *J. Mar. Sci. Eng.* **2023**, *11*, 2238. [CrossRef]
22. Huang, C.; Wang, C.M.; von Herzen, B.; Nguyen, H.P. Development of Novel Offshore Submersible Seaweed Cultivation Infrastructure with Deep-Cycling Capability. *J. Mar. Sci. Eng.* **2025**, *13*, 1958. [CrossRef]
23. Nguyen, H.-P.; Huang, C.; von Herzen, B.; Wang, C.M. Numerical Study on Hydroelastic Responses of Submersible High-Density Polyethylene Circular Seaweed Platforms Held by Single-Point Mooring System and Buoys. *J. Mar. Sci. Eng.* **2024**, *12*, 1437. [CrossRef]
24. Chang, Z.; Zhang, Y.; Zheng, Z.; Wan, R.; Zhang, Z. Development status of the raft-cultivation harvesting devices for kelp. *Fish. Mod.* **2018**, *45*, 40–49. [CrossRef]
25. Liu, F.; Liang, Z.; Zhang, P.; Wang, W.; Sun, X.; Wang, F.; Yuan, Y. Preliminary Discussion on the Development of Saccharina Japonica Offshore Aquaculture in China. *Prog. Fish. Sci.* **2019**, *40*, 161–166. [CrossRef]
26. Yan, J.; Fang, J.; Wang, R.; Wang, W. Preliminary Study on the Single Rope Aquaculture Mode of Saccharina Japonica in the Sanggou Bay. *J. Fish. Sci. China* **2024**, *31*, 1230–1239. [CrossRef]
27. Zhang, Y.; Chang, Z.; Zheng, Z.; Yang, J. Harvesting Machine for Kelp Culture in Floating Raft. *Aquac. Eng.* **2017**, *78*, 173–179. [CrossRef]
28. Yellow Sea Fisheries Research Institute. *Culture of Kelp (Laminaria japonica) in China*; Yellow Sea Fisheries Research Institute: Qingdao, China, 1989.
29. FAO. *Culture of Kelp (Laminaria japonica) in China*; FAO: Qingdao, China, 1989.
30. Gao, D.; Chang, Z.; Zhang, Z.; Zhao, C.; Cheng, S.; Sun, Y. Kelp Harvestng Device. Chinese Patent CN104303697A, 28 January 2015.
31. Zheng, Z.; Chang, Z.; Wan, R.; Yao, Z.; Zhang, Y.; Zhao, D. A Kelp Harvesting Device. Chinese Patent CN109699284B, 30 June 2020.
32. Jiang, T.; Chen, Z.; Zhu, Y.; Hong, Y.; Zou, H.; Tan, Y.; Yan, W. Design of kelp harvest and transfer device. *Fish. Mod.* **2020**, *47*, 16–23. [CrossRef]
33. Jiang, T.; Zhu, Y.; Zou, H.; Lin, L.; Chen, C.; Zhang, Y.; Hong, Y. Kelp Collecting and Transferring Device After Harvesting. Chinese Patent CN107651461B, 12 April 2019.
34. Tullberg, R.M.; Nguyen, H.P.; Wang, C.M. Review of the Status and Developments in Seaweed Farming Infrastructure. *J. Mar. Sci. Eng.* **2022**, *10*, 1447. [CrossRef]
35. Ministry of Agriculture and Rural Affairs of the People's Republic of China. *Agricultural Industry Standard of the People's Republic of China–Classification of Agricultural Machinery*; Ministry of Agriculture and Rural Affairs of the People's Republic of China: Beijing, China, 2024.
36. China's State Council. *Notice of the State Council on Issuing the Action Plan for Prevention and Control of Water Pollution*; China's State Council: Beijing, China, 2015.
37. Fang, J.; Zhang, J.; Xiao, T.; Huang, D.; Liu, S. Integrated Multi-Trophic Aquaculture (IMTA) in Sanggou Bay, China. *Aquac. Environ. Interact.* **2016**, *8*, 201–205. [CrossRef]
38. Dong, S.L. Integrated Aquaculture and Structure Optimization. In *Aquaculture Ecology*; Dong, S.L., Tian, X.L., Gao, Q.F., Dong, Y.W., Eds.; Springer Nature: Berlin/Heidelberg, Germany, 2023; pp. 335–367.
39. Liu, D.; Xing, W. Analysis of China's Coastal Zone Management Reform Based on Land-Sea Integration. *Mar. Econ. Manag.* **2019**, *2*, 39–49. [CrossRef]
40. Ma, Y.; Hu, A.; Yu, C.P.; Yan, Q.; Yan, X.; Wang, Y.; Deng, F.; Xiong, H. Response of Microbial Communities to Bioturbation by Artificially Introducing Macrobenthos to Mudflat Sediments for in Situ Bioremediation in a Typical Semi-Enclosed Bay, Southeast China. *Mar. Pollut. Bull.* **2015**, *94*, 114–122. [CrossRef]
41. Fang, J.; Sun, H.; Yan, J.; Kuang, S.; Li, F.; Gary, F.N.; Jon, G. Polyculture of Scallop Chlamys Farreri and Kelp Laminaria Japonica in Sungo Bay. *Chin. J. Oceanol. Limnol.* **1996**, *14*, 322–329. [CrossRef]
42. Yellow Sea Fisheries Research Institute. *IMTA Good Aquaculture Practice*; Yellow Sea Fisheries Research Institute: Qingdao, China, 2019.
43. Grant, J.; Cranford, P.J. Carbon and Nitrogen Scope for Growth as a Function of Diet in the Sea Scallop Placopecten Magellanicus. *J. Mar. Biol. Assoc. United Kingd.* **1991**, *71*, 437–450. [CrossRef]

44. Fang, J.; Funderud, J.; Qi, Z.; Zhang, J.; Jiang, Z.; Wang, W. *Sea Cucumbers Enhance IMTA System with Abalone, Kelp in China*; Global Seafood Alliance: Portsmouth, NH, USA, 2019.
45. Neori, A.; Gordin, H. Ulva Lactuca Biofilters for Marine Fishpond Effluents II. Growth Rate, Yield and C:N Ratio. *Bot. Mar.* **1991**, *34*, 483–489. [CrossRef]
46. Cohen, I.; Neori, A. Ulva Lactuca Biofilters for Marine Fishpond Effluents I. Ammonia Uptake Kinetics and Nitrogen Content. *Bot. Mar.* **1991**, *34*, 475–482. [CrossRef]
47. Shumway, S.E. A Review of the Effects of Algal Blooms on Shellfish and Aquaculture. *J. World Aquac. Soc.* **1990**, *21*, 65–104. [CrossRef]
48. Landmann, J.; Flack, C.; Kowalsky, U.; Wüchner, R.; Hildebrandt, A.; Goseberg, N. Hydrodynamic Coefficients of Mussel Dropper Lines Derived from Large-Scale Experiments and Structural Dynamics. *J. Ocean Eng. Mar. Energy* **2024**, *10*, 175–192. [CrossRef]
49. Landmann, J.; Fröhling, L.; Gieschen, R.; Buck, B.H.; Heasman, K.; Scott, N.; Smeaton, M.; Goseberg, N.; Hildebrandt, A. Drag and Inertia Coefficients of Live and Surrogate Shellfish Dropper Lines under Steady and Oscillatory Flow. *Ocean Eng.* **2021**, *235*, 109377. [CrossRef]
50. Raman-Nair, W.; Colbourne, B.; Gagnon, M.; Bergeron, P. Numerical Model of a Mussel Longline System: Coupled Dynamics. *Ocean Eng.* **2008**, *35*, 1372–1380. [CrossRef]
51. Gagnon, M. Status of Off-Bottom Mariculture in Wave-Exposed Environments. Part 2. Comparative Loading and Motion of Longline Designs Currently Used in Exposed Commercial Farms. *Front. Aquac.* **2024**, *3*, 1422173. [CrossRef]
52. Buck, B.H.; Troell, M.F.; Krause, G.; Angel, D.L.; Grote, B.; Chopin, T. State of the Art and Challenges for Offshore Integrated Multi-Trophic Aquaculture (IMTA). *Front. Mar. Sci.* **2018**, *5*, 165. [CrossRef]
53. Xue, D.; Wu, Z.; Wu, H. Methods for enhancing the value of Ezo scallops through bottom seeding 2010. *Fish. Sci.* **2010**, *29*, 297–301.
54. Chinese Society of Fisheries. Technological Innovation Drives Zhangzi Island's Global Expansion. Available online: https://www.csfish.org.cn/mobile/article/1621-173 (accessed on 16 September 2026).
55. Fujian Provincial Government. Strengthening Our Work on the Ocean: An Overview of Fujian's Efforts to Promote High-Quality Development of the Marine Economy. Available online: https://fgw.fujian.gov.cn/ztzl/hxlsjjsyqzt/lsdt/202508/t20250818_6992632.htm (accessed on 28 November 2025). (In Chinese)
56. Fujian Provincial People's Government. Toward the Deep, the Far, and the Blue: Three Dimensions Illustrating How Fujian Strengthens Its Marine Innovation Capacity. Available online: https://www.fj.gov.cn/xwdt/fjyw/202506/t20250612_6924065.htm (accessed on 28 November 2025). (In Chinese)
57. The State Council of the People's Republic of China. *National Marine Economy Development Plan for the 12th Five-Year Period*; The State Council of the People's Republic of China: Beijing, China, 2012.
58. The State Council of the People's Republic of China. Opinions on Accelerating the Development of Deep-Sea and Far-Sea Aquaculture. Available online: https://www.gov.cn/zhengce/zhengceku/202306/content_6886007.htm (accessed on 28 November 2025).
59. Dong, S.; Dong, Y.; Huang, L.; Tian, X.; Han, L.; Li, D.; Cao, L. Toward Offshore Aquaculture in China: Opportunities, Challenges and Development Strategies. *J. Fish. China* **2023**, *47*, 039601. [CrossRef]
60. Wenhai Surveying & Mapping Technology Co., Ltd. *Luoyuan County Bili Township Open-Sea Aquaculture Sea-Use Demonstration Report*; Wenhai Surveying & Mapping Technology Co., Ltd.: Wuhan, China, 2025.
61. Fuzhou Municipal Government. All-Scale Protection of Marine Ecological Sea-Area and Scale Aquaculture Moving into Deep-Sea: Breakthrough in Lianjiang's Pilot Reform for Marketising Ecological Products. Available online: https://www.fuzhou.gov.cn/zgfzzt/shbj/xxgk/ztzl/zysthjbhdcjxs/dcdt/201907/t20190730_2997043.htm (accessed on 3 December 2025). (In Chinese)
62. Fuzhou Gulou District People's Government. Fuzhou's "Experimental Fields" Praised by the State Council: Ecological Practices Ready for Replication Nationwide. Available online: https://www.gl.gov.cn/xjwz/ttxw/202012/t20201209_3740896.htm (accessed on 3 December 2025). (In Chinese)
63. Mo, S.; Wang, B.; Zou, J. Breakthrough Achieved in Lianjiang's Pilot Reform on Marketizing Ecological Products. Available online: https://news.fznews.com.cn/dsxw/20190729/5d3f0bdf0eeab.shtml (accessed on 3 December 2025). (In Chinese)
64. Xinhua News Agency. Shandong Weihai: Small Kelp Expands into the Deep and Distant Sea. Available online: https://news.qq.com/rain/a/20240520A08WC300 (accessed on 3 December 2025). (In Chinese)
65. Fujian Provincial Development and Reform Commission. Lianjiang's "Seaweed Core" Receives National Certification. Available online: https://fgw.fujian.gov.cn/ztzl/hxlsjjsyqzt/lsdt/202408/t20240829_6508116.htm (accessed on 3 December 2025). (In Chinese)
66. Li, W.; Wang, Z.; Cui, Q.; Sun, X.; Huang, H. Coastal Ecological Disasters Triggered by an Extreme Rainfall Event Thousands of Kilometers Inland. *Commun. Earth Environ.* **2024**, *5*, 238. [CrossRef]
67. The Paper. Shandong Weihai: Small Kelp 'Bursts Forth' into Deep Sea. Available online: https://m.thepaper.cn/newsDetail_forward_19198790 (accessed on 3 December 2025).

68. Peteiro, C.; Sánchez, N.; Dueñas-Liaño, C.; Martínez, B. Open-Sea Cultivation by Transplanting Young Fronds of the Kelp Saccharina Latissima. *J. Appl. Phycol.* **2014**, *26*, 519–528. [CrossRef]
69. Peteiro, C.; Sánchez, N.; Martínez, B. Mariculture of the Asian Kelp Undaria Pinnatifida and the Native Kelp Saccharina Latissima along the Atlantic Coast of Southern Europe: An Overview. *Algal Res.* **2016**, *15*, 9–23. [CrossRef]
70. Buck, B.H.; Nevejan, N.; Wille, M.; Chambers, M.D.; Chopin, T. Offshore and Multi-Use Aquaculture with Extractive Species: Seaweeds and Bivalves. In *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*; Buck, B.H., Mangan, R., Eds.; Springer: Cham, Switzerland, 2017; pp. 23–69.
71. Bak, U.G.; Mols-Mortensen, A.; Gregersen, O. Production Method and Cost of Commercial-Scale Offshore Cultivation of Kelp in the Faroe Islands Using Multiple Partial Harvesting. *Algal Res.* **2018**, *33*, 36–47. [CrossRef]
72. Chen, Z.X.; Guo, G.X.; Zhuang, B.L. Research Status and Development Tendency of Deep Sea Aquaculture Equipments: A Review. *J. Fish. China* **2023**, *47*, 019602. [CrossRef]
73. Lian, Y.; Ma, J.; Li, D.; Zheng, J.; Tao, A.; Chen, W.; Zhang, J.; Yim, S.C. Experimental Investigation on Wave Attenuation Capacity of Kelp Farms. *Ocean Eng.* **2025**, *337*, 121906. [CrossRef]
74. Lian, Y.; Pan, Z.; Zheng, J.; Zhu, J.; Shen, S.; Shi, J.; Yu, J. Dynamic response analysis of offshore moored kelp farms. *J. Hohai Univ.* **2023**, *51*, 107–116. [CrossRef]
75. Lian, Y.; Boamah, S.O.; Pan, Z.; Zheng, J.; Chen, W.; Ma, G.; Yim, S.C. Engineering Design and Economic Analysis of Offshore Seaweed Farm. *Front. Mar. Sci.* **2024**, *11*, 1276552. [CrossRef]
76. Yang, C.; Hu, A.; Zhang, H.; Chen, H. Numerical Study on Flow Characteristics, Hydrodynamics, and Structural Response of an Integrated Aquaculture Platform with WECs and Wind Turbine. *Ocean Eng.* **2026**, *343*, 123423. [CrossRef]
77. Karathanasi, F.E.; Soukissian, T.H.; Hayes, D.R. Wave Analysis for Offshore Aquaculture Projects: A Case Study for the Eastern Mediterranean Sea. *Climate* **2022**, *10*, 2. [CrossRef]
78. Li, H.; Liu, Y.; Liang, B.; Liu, F.; Wu, G.; Du, J.; Hou, H.; Li, A.; Shi, L. Demands and Challenges for Construction of Marine Infrastructures in China. *Front. Struct. Civ. Eng.* **2022**, *16*, 551–563. [CrossRef]
79. State Council of the People's Republic of China. Opinions of the General Office of the State Council on Practicing the "Big Food" Concept and Building a Diversified Food Supply System. Available online: https://www.gov.cn/gongbao/2024/issue_11606/202409/content_6976938.html (accessed on 15 December 2025).