Review

Review of Artificial Downwelling for Mitigating Hypoxia in Coastal Waters

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Abstract: Hypoxia is becoming a serious problem in coastal waters in many parts of the world. Artificial downwelling, which is one of the geoengineering-based adaptation options, was suggested as an effective means of mitigating hypoxia in coastal waters. Artificial downwelling powered by green energy, such as solar, wind, wave, or tidal energy, can develop a compensatory downward flow on a kilometer scale, which favors below-pycnocline ventilation and thus mitigates hypoxia in bottom water. In this paper, we review and assess the technical, numerical, and experimental aspects of artificial downwelling all over the world, as well as its potential environmental effects. Some basic principles are presented, and assessment and advice are provided for each category. Some suggestions for further field-based research on artificial downwelling, especially for long-term field research, are also given.

Keywords: artificial downwelling; hypoxia; environmental impacts; coastal waters; dissolved oxygen

1. Introduction

Due to global warming and coastal eutrophication, the coastal waters that are usually associated closely with intensive human activities are facing hypoxia, or low dissolved oxygen concentrations, representing a significant threat to the health and economy of coastal ecosystems [1–4]. Individuals of immobile species, such as oysters, mussels, and sea cucumber, have no capacity for escaping low-oxygen areas and are especially vulnerable to hypoxia [5–7]. These organisms can become stressed and may die in low-oxygen conditions. Fish deaths can also result from hypoxia, especially when the concentration of dissolved oxygen drops rapidly, resulting in significant impacts on marine food webs and the economy [8]. Hypoxia is hazardous for benthic habitats; it alters the nutrient cycling, reduces the biodiversity of marine communities, and often leads to the blooming of harmful blue-green algae [2,9].

The dynamics of coastal hypoxia is rather complex [10,11]. Although coastal hypoxia can be caused by natural processes, such as stratification and hydromorphology [2,12,13], the dramatic increase in the number of world coastal waters developing hypoxia is linked to anthropogenic factors, such as eutrophication and global climate change resulting from human activities [14]. More than 400 persistently or seasonally hypoxic regions have been reported in the coastal waters of the world [15], covering an area of 245,000 km² [3]. It is reported nowadays that major fishery areas—the Baltic, Kattegat, North Adriatic, Black Sea, Gulf of Mexico, and the East China Sea—are suffering ecological degradation and loss of biomass as a result of coastal hypoxia [3,7,16,17].
While nutrient load reduction plays a fundamental role in environmental management for coastal hypoxia [2,18], eutrophication management faced recalcitrant challenges with little success over the past 30 years; the problem of eutrophication is still unclear in terms of the physical environment [19], ecosystem characteristics, nutrient sources, socio-economic driving forces, and governance measures. Hypoxia in marine ecology urgently needs to be alleviated, especially in the field of marine fisheries [20].

Artificial downwelling systems, which is one of the geo-engineering-based adaptation options, are recognized as an important support for these plans and for the subsequent mitigating hypoxia in coastal waters [21]. Artificial downwelling, as an engineering solution to coastal hypoxia, powered by green energy, such as solar, wind, wave, or tidal energy, can develop a compensatory downward flow on a kilometer scale, favoring below-pycnocline ventilation and thus mitigating hypoxia in bottom water. This may be the most realistic alternative for mitigating hypoxia in coastal waters in the future [22].

Artificial downwelling transports oxygen-rich surface waters into oxygen-deficient deeper layers [23], strengthen the below-pycnocline ventilation, increase the dissolved oxygen concentration in the bottom waters, and consequently mitigate bottom hypoxia. Most studies to date yielded positive results with respect to artificial ocean downwelling: (1) Well-designed artificial downwelling systems maintained stratification and did not significantly increase bottom water temperature; therefore, in stratified oceans, the thermocline remained stable and the process preserved a cold-seawater fishery habitat for acrobenthic communities [24]; (2) levels of dissolved oxygen concentration (DO) were usually elevated in bottom waters [25]; and (3) concentrations of iron, methane, phosphorus, nitrogen, and hydrogen sulfide were shown to decrease in bottom waters and sediments [26].

Therefore, techniques for artificial downwelling are being researched, with many new devices and equipment in development. Recently, institutions and scientists dedicated great efforts to the research of artificial downwelling, with great progress being made and techniques addressing such issues including density current generators, wind-powered pumps, wave-powered pumps, and current-induced artificial downwelling. The aim of this paper is to review available technologies to pump oxygen-rich surface waters into oxygen-deficient bottom waters to mitigate hypoxia in coastal waters, and to suggest procedures for future research. We also assessed the potential benefits and risks associated with these artificial downwelling technologies.

2. Artificial Downwelling Technologies

Many concepts exist regarding artificial downwelling; over 60 artificial downwelling techniques are patented throughout the USA, Japan, Europe, and China. As summarized in Table 1, despite this large variation in design, artificial downwelling technologies are generally categorized by energy source and can be classified into four predominant types:

1. Density current generator (DCG), powered by thermal energy, to bring surface water down and bottom water up to an intermediate layer. A wide-area survey of the seafloor at Gokasho Bay, Japan, in 2006, where a DCG worked for ten years, confirmed the DCG effects of avoiding hypoxia and improving benthos [27].

2. Wind-powered pump. Wind energy is used to overcome the density structure of the ocean and pump warm, oxygen-rich surface water into the bottom sea layers (BOX project) [21].

3. Wave-powered pump, such as WEBAP and OXYFLUX, for artificial downwelling. These pumps are thought to counteract oxygen depletion in the bottom layers by pumping oxygen-rich surface water downward to a desired depth around the halocline, driven by the action of small waves [28,29].

4. Current-induced artificial downwelling. Semi-diurnal tidal currents exist in many coastal areas, estuaries, and their adjacent areas. This method utilizes the kinetic energy of the surface current to drive downwelling flow to improve DO condition in bottom waters [30].
Table 1. Different types of artificial downwelling devices.

| Engineering Techniques | Power Supply | Application Site | Simulation | Experiment | Sea Trial |
|------------------------|--------------|------------------|------------|------------|-----------|
| DCG [31]               | Thermal energy | Gokasho Bay, Japan | MEC Ocean Model | Rotating hydraulic model experiment | About 12 years in operation |
| BOX [21]               | Wind energy | By Fjord of Baltic sea | To be studied | To be studied | Run for 2 and a half years |
| WEBAP [28]             | Wave energy | The Baltic Sea | To be studied | Wave mooring response | Run for more than 2 years |
| OXYFLUX [21]           | Wave energy | North Adriatic Sea in the Mediterranean | CFD-RANS code and overset grid method | Experiments on devices response to wave | To be conducted |
| Tidal pump [30]        | Tidal energy | Changjiang Estuary, China | CFD-k-ε turbulence model | Layered experiment and optimization experiment | To be conducted |

2.1. Density Current Generator (DCG)

A prototype device of ocean artificial downwelling named a density current generator (DCG), i.e., an electrical pump powered by solar energy and fossil fuel, was proposed by the University of Tokyo and was developed and moored in the Hazama Inlet of Gokasyo Bay, Japan [32,33], where the red tide was insignificant since the installation of the apparatus in 1997 [27].

The DCG system, which was designed with a steel riser pipe and an electrical pump of great power, mixes surface and bottom waters with density control [27]. The mixture then discharges to a neutral-buoyancy depth via the ring-nozzle by the motor-driven impeller installed in the pump casing. The discharged water is quickly mixed with the middle layer, which has a significant entrainment rate of 10 times [34]. The flow rate of 120,000 m$^3$/day, generated by electric power of only 12 kW, with the aim of improving water quality in Gokasho Bay, Japan has a good effect during actual operation [31]. The system operated successfully for more than 12 years, and long-term observations confirmed the positive effects of the DCG in increasing the abundance and biomass of benthos and reducing the volume of hypoxic bottom water. However, the low energy consumption efficiency and the high construction and maintenance expenses of the system make it uneconomic for large-scale or sustainable applications [35].

2.2. Wind-Powered Pump

In the Baltic Sea, there are 6000 square kilometers of continually expanding hypoxic zone, which is now about four times the area observed in 1960 [36], making the Baltic Sea one of the most serious regions of hypoxia [37]. Studies have shown that, in addition to climate warming, loads of continental nutrients have caused an increase of eutrophication in the last 50–100 years [38], which is the key to the increasing severity of hypoxia [39]. This lack of oxygen in the Baltic Sea caused huge ecological damage and economic losses [40].

Stigebrandt and Gustafsson carried out an ecological project called BOX [21] (Baltic deep-water Oxygenation) in By Fjord on the western coast of Sweden, where a strong permanent halocline and serious hypoxia problem exists (as shown in Figure 1) [28]. This project designed 100 offshore-wind-powered pump to bring oxygen-enriched water from 50 m to 125 m [41], with each pump providing 0.6 kW of power and pumping 100 kg of water to the lower layer every second [42]. The calculation is aimed at the Baltic Sea; hence, it needs to be recalculated for other conditions according to the method provided by Ander et al. Stigebrandt et al. employed the wind-pump system for two and a half years, showing it to be significantly effective [42,43].
Figure 1. (a) Map of the Baltic Sea. (b) Vertical distribution of hypoxia in the Baltic Sea [36].

Figure 2 shows the wind-pump system, with the wind turbine generating electricity on the working platform and delivering power to two pumping systems that connect to the upper end of the downwelling pipes; the lower end of the pipes is fixed to the seabed by an anchor chain. The water inlet is set at 2 m below the sea surface, and the water outlet is set at 6 m above the seabed. Surface water is drawn into the downwelling pipe and pumped down. The discharged surface water is mixed and entrained with submarine water then rises to neutral buoyancy in the hypoxia zone and spread horizontally.

Figure 2. Schematic diagrams of the wind-powered pumping system [40], (a) The two pumping systems. (b) Underwater structure of pump.

2.3. Wave-Powered Pump

The concept of wave utilization to pump well-oxygenated surface water was proposed for the Baltic Sea and the North Adriatic Sea [29,44]. Christopher Carstens first proposed a wave-energized aeration pump for the Baltic Sea hypoxia problem (WEBAP) in 2008. The physical principle of the WEBAP is that a floating breakwater should collect incoming waves into a reservoir inside the breaker. The waves hit and run up the slope of the floating breakwater until an overtopping event occurs. This process yields the potential energy in the reservoir, which in turn forces surface water into the desired depth around the halocline [45]. Through linear wave theory and energy analysis, Carstens investigated and calculated the mean and median energy flux of the Baltic Sea wave power, concluding that, combined with the amount of power needed to oxygenize the Baltic Sea estimate by Anders Sriggebrandt et al. [21], the efficiency of the breakwater (as shown in Figure 3) to solve the problem of anoxia was evaluated [28]. This project is expected to cost 16 million euros.
Antonini et al. proposed a concept for a wave-driven device in 2012, named OXYFLUX in 2015, for artificial downwelling and suggested the possibility of downwelling surface seawater by using wave energy to solve the problem of eutrophication and hypoxia in the North Adriatic Sea [46]. Wave energy is used to invert the density structure of the ocean and force oxygen-rich surface water into the oxygen-depleted bottom layers [47].

The OXYFLUX consists of a truncated-conical floater, a downwelling pipe, and a stabilizing ring [46]. The buoyancy of the whole structure is entrusted to a truncated-conical floater, which keeps the structure afloat as well as collects water from overtopping [48]. The connection with the bottom, where a stabilizing ring is mounted, is fastened by means of a rigid pipe. Kofoed (2002) identified the optimal slope angle to maximize the overtopping discharge for a linear structure ramp as 30°. For the OXYFLUX, the floater ramp slope was designed to be 25.3° to maximize the overtopping discharge according to the buoyancy needs. The material of the floater has been selected based on the need to guarantee an appropriate level of the free-board crest. The physical principle of the OXYFLUX is very simple. The floater collects incoming waves into a reservoir floating on the sea. Water overtopping yields a higher hydraulic head in the reservoir that can be used to overcome the density difference between the surface and deep water. As a result, oxygen-rich surface water is induced downward through the downwelling pipe. At the bottom of the device, there is a stabilizing ring that has the function of reducing the heave motion by means of the induced viscous dissipation and accordingly facilitates the overtopping.

2.4. Current-Induced Artificial Downwelling

In 2019, Xiao et al. proposed using the kinetic energy of the surface current to invert the density structure of the ocean and pump oxygen-rich surface water into the bottom oxygen-depleted layers by means of a current-induced pump [30]. The Changjiang Estuary, China, is one of the largest areas to suffer seasonal hypoxia in the world [12,49], however, semidiurnal tidal current exists widely throughout the Changjiang Estuary and its adjacent areas, with data from the tide observatory indicating that in the spring tides, the tide may reach a speed of 1–1.6 m/s [50].

The possible tidal pump proposed for this type of artificial downwelling device could have a 90° bend, a vertical downwelling pipe, and a floating platform [30]. On the back of the upper bend is a flow director keeping the pump consistently toward the incident flow direction, with deviations from this direction causing the pump to be unbalanced subject to the moment of horizontal flow, which is an
advantage in bidirectional flow, e.g., tidal power applications. A ballast hanging on the lower end of the pump keeps the downwelling pipe erect as much as possible. When passing over the upper bend inlet of the pump, the horizontal current decelerates due to the blocking effect. According to the Bernoulli principle, this deceleration increases static pressure at the entrance which, if large enough to overcome stratification, drives downwelling flow in the pump. If the tidal current is strong enough to overcome stratification, downwelling flow is produced, evolving into an oxygen-rich buoyant plume below the pycnocline, which offers in situ conditions to experimentally study the related ecological effects of artificial downwelling. Mathematical and hydraulic modeling analyses indicated that a tidal-driven pump for artificial downwelling drives downward flow in the pump at a flow rate ranging from 0.4 to 1.1 m$^3$/s, with a relative density difference between the diluted surface water and the bottom water ranging from 0.004 to 0.008 and a horizontal current reaching its peak at 1.6 m/s.

Fan et al. proposed an improved current-induced pump for artificial downwelling in 2019, which is low-cost, reliable, and easy-to-use for Muping marine ranching, located in Shandong province, China, as shown in Figure 4a,b [51]. Marine ranching plays a significant role in the development of the coastal marine ecology and economy [17]. However, the large-scale death of benthic organisms caused by hypoxic bottom waters results in huge economic losses to marine ranching [52]. Figure 4c shows the time series of the observed dissolved oxygen concentrations of marine ranching in three depths in the summer of 2016. Before 27 August, the bottom water appeared hypoxic, causing hundreds of millions of CNY (Chinese yuan) loss. In order to reduce the loss caused by hypoxia, Fan et al. (2019) further optimized the structure of the tube based on the theories of Xiao et al. (2018) by adding the concrete base and mixer, thus enhancing the efficiency of the downwelling device and its applicability in marine ranching.

Fan et al. studied the performance of the device, indicating that with a cross-sectional tube area of only 0.12 m$^2$, a flow rate of 200 m$^3$/h flow rate downwelling was induced when the speed was 0.4 m/s and the density difference was 0.5 kg/m$^3$ [53]. Therefore, the problem of hypoxia could be greatly improved if this device is deployed widely in Muping.

![Figure 4](image_url)

**Figure 4.** The Muping marine ranching situation(a), (b). The data in (c) are for 2016 [54].

The conceptual diagram of this device in the sea is shown in Figure 5. Its main feature is a vertical square tube with a 90° curved head, and the bottom of the square tube is installed on an artificial reef to fix it to the seabed. There are also static mixers installed on both sides of the device, allowing surface water to flow out from the bottom of the pipe and pass through two wing-like guide plates to fully mix with the surrounding water so that it can diffuse in the hypoxic area. The downwelling flow rate generated by this device is proportional to the equivalent diameter and bending radius of the tube and is inversely related to the length of the tube. Compared to round tubes, square tubes exhibit a larger flow cross-section with the same diameter.
3. Overview of Numerical Studies for Artificial Downwelling

Computational Fluid Dynamics (CFD) applies various discrete mathematical methods to conduct numerical experiments, computer simulations, and analytical studies on various types of fluid mechanics problems. A recent development in CFD enables us to predict the effects of artificial downwelling in hypoxic areas.

Researchers conducted numerical simulations on the hydrodynamics to investigate whether the DCG is applicable to Isahaya Bay in Ariake Bay, Japan, which is facing massive environmental problems produced by a dyke built in Isahaya Bay [55,56]. The purpose of the numerical study was to determine if the DCG, from which water is discharged at the amount of 0.5 megatons per day at its realistic maximum, can reduce oxygen-deficient water in such a large bay. The computations were carried out for the large spatial scale of Ariake Bay by using a three-dimensional numerical code called the MEC Ocean Model, which was verified by a laboratory-scale rotating hydraulic model (Section 4.1.3), and the hydrostatic model is nested in nonhydrostatic model to simulate the appropriate intrusion depth of mid-density water discharged in stratification [51]. The numerical grid is developed based on the hydrostatic and the full-3D models [57], with contours indicating the topography of Ariake Bay. In the simulation, the DCG was deployed at the north of the mouth of Isahaya Bay, where hypoxia in summer frequently presents. The numerical results showed that the seawater discharged from the apparatus spread in the head of Ariake Bay within a couple of weeks, and apparatus of DCG has the capacity of reducing up to 70% of oxygen-deficient water in Isahaya Bay [56].

Other numerical simulations were also conducted regarding the ecological effects of the DCG [56], the physical model that used the MEC Ocean Model [58], with the ecosystem models [59]. This model consisted of both pelagic and benthic models and confirmed that DCG can effectively reduce about 70% oxygen-deficient water in a semi-enclosed bay, thereby showing its potential role in improving primary productivity in the sea [60].

Antonini et al. (2016) conducted numerical experiments simulating the OXYFLUX pumping capacity for artificial downwelling by using a CFD-RANS code and an overset grid method. A series of simulations were performed to investigate nonlinear effects due to interactions between waves and the OXYFLUX model and the performance of OXYFLUX in regular waves [61]. The CFD model showed good agreement with the measured data of the heave decay test under the action of regular waves; the error of the heave decay period was 3.7%. Moreover, the simulation results showed that “nonlinear effects remarkably reduce the dynamic behavior of the OXYFLUX and generate an unexpected second
harmonic for pitch response intensifying the overtopping discharge also for small waves caused by the summer’s low-intensity winds” [61]. The design of the bottom stabilizing ring increases the OXYFLUX pumping capacity with the increase of the viscous dissipation, reduces the amplifier response of the floater, and induces a phase shift between the incoming wave and the heave motion, which facilitating the overtopping.

Xiao et al. (2019) focused on the total entrained (TE) flow rate of artificial downwelling representing the magnitude of entrainment transport [62]. A verified standard $k-\varepsilon$ turbulence model, in which different initial pipe flow speeds, density differences, and pipe radii were involved, was applied to characterize the hydrodynamic performance of the injection of a negatively buoyant jet from a round pipe into a stagnant, homogeneous ambient medium [63].

The evolution of entrainment transport for artificial downwelling was simulated, in which the negatively buoyant plume first reaches its maximum penetration, and then moves back to the steady point [53]. The plume in the steady state is divided into two regions according to the type of leading forces exerted on the plume. In the interaction region [62], the initial jet interacts with the reverse main flow, where the entrainment dynamics are governed by momentum flux and buoyancy flux [64]. The results of the numerical studies showed that the ratio of the terminal total entrained flow rate to the initial jet flow rate first decreased as either the initial jet velocity or the relative density difference became larger, but then increased. Increasing the pipe diameter continuously reduced the ratio.

4. Overview of the Experimental Studies for Artificial Downwelling

4.1. Laboratory Experiments of Artificial Downwelling Systems

4.1.1. Laboratory Experiments of WEBAP

In order to study the ability of a wave-induced downwelling device (WEBAP) to relieve hypoxia, a series of experiments was carried out in the deep wave tank of the Hydraulic and Coastal Engineering Laboratory of Aalborg University by Margheritini in 2011 [44]. The experiment was equipped with wave gauges to measure the parameters of waves generated by AwaSys software, an displacement sensor to measure the movement of the device body under waves including roll, pitch, yaw, and accelerations in the three directions, a propeller to measure flow velocity inside the pipe, and load cells on the mooring lines to measure the cable force. The remarkable conclusion was that in the WEBAP model with a prototype length of 13.5 m and a scale ratio of 1:25, the natural frequency for surge corresponding to 2.5 s, 20 s for heave, and 2.8 s for pitch in free oscillation tests. Model experiments show that the movements of the floating body induced by the wave have a negative effect on the overtopping, with the maximum mooring force of 102.9 kN on the front mooring, which is twice bigger than the rear mooring force of 51.11 kN. The higher overtopping occurs for slope angles between 23° and 35°, and 23° is suggested by the developer.

4.1.2. Laboratory Experiments of OXYFLUX

In order to investigate the efficiency of floating OXYFLUX devices aiming to pump oxygen-rich surface water downward to deep layers, Antonini et al. conducted a model experiment in 2012 to study the effects of both rigid and flexible downflow pipes, as well as different wave parameters and mooring systems. The velocity of the downward flux was measured by a Doppler Profiler (DOP) sensor which was mounted in the center of the duct. The vertical circulation cells and floater displacements are estimated by injecting dye and video-recording. Research showed that the mooring system (use chains or cables) largely affects the movements of the tested devices and the efficiency of pumping water downwards increases by using two pretensioned nylon cables [29]. Floating is more important to the flexible device than the rigid one, the reason is that the rigid one has larger inertia and affects more the dynamic response of the OXYFLUX device. Moreover, the flexible device is quite light and has no effect on dynamic behavior. Hence, the floater shape and mass govern the dynamic response [29].
Antonini et al. carried out further experiments in the wave flume at the Hydraulic Laboratory of the University of Bologna in 2015 [46], analyzing the submergence percentages and the dynamic responses of different mooring method, elastic cables, and chains, which are evaluated by the image processing analysis method. Eventually, they reached a conclusion that the flux of the pumped water mainly depends on the ratio of incident wave height to device freeboard. Recommendations for the design of the OXYFLUX were also given according to the conclusion [44].

4.1.3. Laboratory Experiments of DCG

In order to study whether the DCG devices can alleviate the problem of large-scale hypoxia in Ariake Bay, Sato et al. conducted a laboratory-based, rotating hydraulic model experiment to compare with a simulation. The physical pictures of the experimental device include a topographic model for Ariake bay in a circular rotating tank [65], with a float-type tide generator at its periphery; the DCG device was designed in the experiment to discharge mid-density dyed water to the pycnocline. In this way, the areal concentration of DCG flow could be observed horizontally by the luminance method with a digital video camera, and the tidal residual current could be obtained by the PIV (Particle Image Velocimetry) stain tracer method to analyze the flow structure in the bay. This experiment that can analyze the environmental impact of DCG at a large scale was used to verify the DCG simulation discussed in Section 3 [66].

4.1.4. Laboratory Experiments of the Tidal Pump Devices

Research on the tidal-driven artificial downwelling was conducted by Zhejiang University since 2018 [30]. This research mainly focused on designing a robust and high-efficiency artificial downwelling system. Research on the theoretical analysis of build-up models, considering the flow characteristics of downwelling [67], suggested that the system capacity and efficiency were functions of the geometrical parameters of the downwelling pipe, tidal current speed, relative density difference, the immersed length of the pump below the pycnocline, and the pump geometry [48]. To confirm the theoretical model and the performance of the tidal-powered artificial downwelling system [68], scale model experiments were conducted in the flume at the Offshore Laboratory of Zhejiang University, China, by Xiao et al. (2018). A 1:80 model was designed to study downwelling pipe a 20 m in length submerged in a waterbody 30 m deep, covering a wide range of tidal current speeds from 1.12 to 2.12 m/s and with density difference heads from 1.2 to 6.4 cm.

Fan et al. conducted another experiment to improve the current-induced pump in a two-layer stratified flume at the Hydraulics Laboratory at Zhejiang University, China (2019). As Figure 6 shows [54], the tube was designed to have a square cross-section of PVC material, and the mathematical relationship between the downwelling flow rate and the tidal current velocity, the equivalent diameter radius, the bend radius of the pipe, and the density difference was subsequently proven [69].
were used to monitor the temperature, salinity, and oxygen concentration in real-time, and passive water was pumped to an anoxic zone at a depth of 35 m, about 6 m above the seabed. During the winter due to the disappearance of stratification. This system promoted the eco-environment to be better and eliminated the hypoxic water gradually, which was proven by the disappearance of red tide phenomenon and increased seaweed and benthos. The results of the long-term sea trial showed that DCG systems have excellent potential to reduce the impact of hypoxia in a semi-enclosed water body.

4.2.2. Sea Trial of BOX System

Stigebrandt et al. conducted a wind-powered artificial downwelling device sea trial (BOX) at By Fjords in the Baltic Sea from October 2010 to December 2012. The test location is shown in Figure 7, and the device uses two electrically powered units for tow downcomers that are 32 m long and 0.8 m in diameter (Figure 2a). During the 12,000 h of operation of the device, 86 million cubic meters of surface water was pumped to an anoxic zone at a depth of 35 m, about 6 m above the seabed. During the operation of the device, Seabird loggers and AADI (Aanderaa Data Instruments) oxygen optodes were used to monitor the temperature, salinity, and oxygen concentration in real-time, and passive samplers, sediment profile imagery (SPI), and other devices also used to periodically measure changes in hydrogen sulfide, nutrient concentrations, particulate organic carbon, chlorophyll-a, etc. at several test depths. The effect of the wind-powered device on the ecological environment at the bottom of the test area was studied. When the bottom red line indicating the operation of the device appeared, the oxygen concentration in the water significantly increased alongside other biogeochemical changes such as an 80% decrease in the content of phosphate, replacement of hydrogen sulfide by oxygen, as well as the increase in species richness.
5. Environmental Effects of Artificial Downwelling

The phenomenon of hypoxia and its ecological effects on the global scale have been extensively studied, the practical application of artificial oxygenation technology has been advanced in the past 20 years, however, the ecological benefits of artificial downwelling technology are even less researched. Hypoxia in the bottom waters promotes the release of phosphate and nitrogen from the sediment, aggravating the degree of eutrophication and causing a vicious circle that can further expand oxygen consumption. Among this ecological impact, artificial downwelling technology has been considered as an engineering method to relieve hypoxia.

Among several artificial downflow technologies, DCG and BOX projects have been carried out for decades, and some studies have focused on the impact of devices on the ecological environment. In 2007, Otsuka et al. conducted field surveys on the environmental restoration of the DCG device that had been operating in Gokasho bay for 10 years; water quality, sediment, and seaweed distribution in the sea trials area Hasamaura and the control area Shimotsuura were investigated [73]. The results showed that in the sea trials area the density of seawater no longer has discontinuous stratification, and the oxygen in the bottom is more than 6 mg/L in summer while the control area is less than 4 mg/L. The seabed sediment changes from muddy to sandy and, at the same time, the amount of seaweed is twice that of the control area in winter, then the amount of seaweed is halved in summer, while seaweed disappears in the control sea area [27,60,70].

Stigebrandt analyzed the ecological effects of the BOX device based on the results of the sea trial [72], showing that the artificial downwelling is a possible technique to increase the dissolved oxygen concentration in the water column of the By Fjord and reduce phosphorus spill from sediment by pumping the oxygen-rich surface water into the oxygen-depleted bottom water. Forth et al. further conducted a genetic analysis of the fjord waters operated by the wind-driven downwelling device to study the microbial community dynamics [74]. By extracting DNA from water samples, they found that salinity and oxygen concentrations are the main reason for the differences in hypoxic communities and surface communities. In addition, ammonium, hydrogen sulfide, and phosphate were also shown to have impacts [75]. Most importantly, the transformation of anaerobic bacterial communities to aerobic bacterial communities was discovered, leading to the conclusion that large-scale aeration projects simulate natural oxygenation events and alleviate water hypoxia [76,77].

The above results show that artificial downwelling can alleviate the hypoxia problem in certain ranges; however, the research on the global scale biogeochemical cycle of the downflow device is
still needed. Downwelling technologies may have potential side effects, including the destruction of the stratification of water and changes in the water cycle and the natural biochemical cycle process. Studies on the disturbance of submarine sediments by downwelling indicate that if the critical Froude number associated with the downwelling flow speed and the discharge position is greater than 0.5, it will cause the resuspension of the sediment, with an increase of water turbidity and phosphorus release in the water column [25]. Potential impacts of the warm surface water and particulate organic matter transporting down need to be studied; downflow efficiency may be reduced due to biofouling from long-term operations and competition for space and predation of aquatic organisms may be disturbed [78]. The performance of the 5 downwelling devices discussed in this article is summarized in Table 2.

### Table 2. Comparison of artificial downwelling devices.

| Engineering Techniques | Maintenance | Cost | Oxygen Efficiency | Advantages | Drawbacks |
|------------------------|-------------|------|-------------------|------------|-----------|
| DCG                    | More difficult with mechanical structure | Estimated 15 USD/h with the use of 5 kW/h electric motor impeller [78] | The flow rate of 120,000 m$^3$/day generated by 12 kW electric power | Large discharge water flow with significant effect | Energy unsustainable |
| BOX                    | More difficult with mechanical structure | 261,900 USD for installation and estimated 10-year maintenance | Designed to use 100 devices with 0.6 kW of each power to provide 100 kg/sec water to the Baltic bottom hypoxic zone | High downwelling flow rate | Complex structure |
| WEBAP                  | More difficult with mechanical structure | Projected to cost 1,178,605 Euro | require about 750 floating breakwaters of a length of 50 m each, which can transfer about 10,000 m$^3$/s of surface water | Easy operation with Clean energy | Large device structure |
| OXYFLUX                | Relatively easy | Relatively cheap using clean energy | Surface water can be pumped when the flow rate in the pipe is about 0.3 cm/sec | Running even under small waves of mild season | Need to deploy multiple devices |
| Tidal pump             | Relatively easy | Relatively cheap using clean energy | Using a pipe with a cross-sectional area of 0.12 m$^2$ to pump 200 m$^3$/h of surface water, under the 0.4 m/s of current and 0.5 kg/m$^3$ of density difference | Clean energy and simple structure with low cost | Need to deploy |

### 6. Discussion and Conclusions

In general, the techniques about artificial downwelling for mitigating hypoxia in coastal waters are appropriate and suitable for certain applications. They own unique advantages and drawbacks. This paper has set out the results of the literature review and case study analyses. The purpose and research themes of artificial downwelling, their design, highlighted issues, monitoring, management, and performance have been examined.

The DCG was greatly successful in the ecological restoration of a semi-enclosed bay. It was supported strongly by the Japanese government and the local fisherman cooperative organizations, so the technology matured in regard to operation practice for the last ten years. However, there are also some drawbacks, including (1) it is not cost-effective in practice; (2) the working range of the DCG system is limited by the topography, therefore, if it is applied in enclosed and semi-enclosed water body, the DCG system will get very good effects; (3) The complex mechanical and electrical system and its active control system is needed as the reliability and safety is a big problem in the ocean [79]; (4) the long pipe may be twisted or broken.
A wind-powered artificial downwelling system is probably the most efficient and mature way to mitigate hypoxia in the Baltic Sea. There is enough wind energy to provide unlimited operation time without consideration of power limitation. However, the huge up-front investment and long-term operation and maintenance costs, which will reach 200 million Euros budget, bring a heavy burden to the government and society, and so on [21].

Wave energy conversion is quite feasible for artificial downwelling’s power supply. OXYFLUX is quite a novel way to power artificial downwelling. It was developed for North Adriatic summer conditions (i.e., really small waves), which is reliably and predictably available at all hours. On the other hand, it is necessary to optimize the system structure to improve reliability and efficiency. In this way, the system can access enough density difference head to pump the surface oxygen-rich seawater into the bottom water. The advantage of adopting OXYFLUX is that a complicated structure is unnecessary for the realization of downwelling based on this principle. OXYFLUX is able to work with really small wave heights and pump water with breeze waves (around 0.3–0.5 m wave height). It is worth mentioning that oxygen depletion in the world’s coastal waters primarily caused by density stratification in a body of water. The density stratification will be destroyed and the hypoxia will be mitigated under the combined action of winds and waves.

According to the research of Fan et al. [81], the main question of tubular artificial upwelling is the energy flux balance, which is integrated across the downwelling pipe to assess the effects of head difference, water flow rate, friction loss power in the pipe, and power demand of the water column motion.

Current-induced artificial downwelling system can unlimitedly access to marine energy. On the other hand, compared with the DCG and BOX engineering downwelling devices, the tide-induced downwelling device is simple in structure, convenient in processing, low in cost, and easy to implement, and has the potential to be widely deployed and applied in marine ranching. The tide-induced device for artificial downwelling. Compared with other devices, the simplicity, lack of moving mechanical parts, cheap cost, and reliability are the important advantages that make the tide-induced device useful for applications where semidiurnal tidal current widely exists [82]. However, the limitation is that tidal power is not available globally. Furthermore, the current-induced artificial downwelling technology is strongly limited in the duration of tide and the water flow rate. If such a current-induced artificial downwelling system could be viable for a hypoxia area or marine ranching, a large number of devices would be necessary [83].

Integrated multidisciplinary approaches should be used for the application of artificial downwelling technology and research of its ecological effect. D. Gilbert et al. pointed out the importance of monitoring in the hypoxic area, the effectiveness, and ecological impact, and perhaps potential side effects of downwelling require comprehensive environmental monitoring and analysis of biochemical geophysics [84].

As discussed, the artificial downwelling technologies are the most promising choice as a geoengineering method for mitigating hypoxia in coastal waters. It is a clean, physical process of artificial mixing with no added substances and has a brighter future and more applications.

The artificial downwelling technologies have significantly advanced in recent years. The present situation all over the world shows that the development of a wide variety of artificial downwelling applications, from concept to full-scale sea trial stage, is a difficult, slow, and expensive process. They are possessed with some advantages and limitations and applied in different situations, and their feasibility, survivability, and reliability should be demonstrated [85]. Furthermore, the newness of the concept and the lack of prototype operating experience on which to base designs are a barrier to the implementation of artificial downwelling. Governments tend to be cautious about committing resources to unproven technologies, and private investors are unlikely to commit very large sums of venture capital until the following questions are answered: (1) There is a huge amount of the hypoxia bottom water, so what flow rate would be needed to increase the dissolved oxygen concentration in it and consequently mitigate bottom hypoxia. (2) Would the warm, light, surface ocean water
released near the bottom just rise again to a level above the oxygen-deficient bottom waters? How to trap the oxygen-rich surface ocean water (SOW) at the bottom. (3) Would the oxygen-rich surface ocean water be diluted by mixing to the point where their concentration makes a significant impact on hypoxia? (4) Downwelling a large amount of SOW to the bottom layer requires a massive energy supply, which partly causes its high costs. How much would it cost to construct, deploy, tether, and power very large pumps capable of forcing the required amount of oxygen-rich surface water into the oxygen-deficient bottom waters? In the open ocean where they would be subjected to storms and would get little maintenance? (5) Although the density difference between the surface and bottom water in coastal waters is only about 2–3 kg/m³, the required oxygen-rich surface water is an enormous amount, and the mechanical energy required to overcome it is also huge. Which kind of green energy harnessed from the ocean, in the form of wave, tidal, marine current, and thermal resources, can be used for artificial downwelling systems? (6) What are the potential environmental effects and side effects of artificial downwelling engineering on the marine ecosystem?

Artificial downwelling technologies are new, unproven and their cumulative environmental impacts are not known. Though artificial downwelling is expected to have a little negative impact on the environment, the technologies are too new to gauge all factors. Prolonged studies are needed.

In general, governmental research and development funding for artificial downwelling technologies is increasing. The Japanese government has been implementing the Law Concerning Special Measures for Conservation of Lake Water Quality since 1984. The law requires the implementation of water quality protection plans in relevant areas to alleviate the problems caused by eutrophication and hypoxia [86]. Since the late 1980s, the Convention on the Protection of the Marine Environment of the Baltic Sea (Helsinki Commission [HELCOM]), has been working to reduce the anthropogenic nutrient loads and relieve hypoxia [87]. The 2030 Agenda for Sustainable Development was adopted at the United Nations General Assembly in 2015. The goal of “protecting and sustainable use of oceans and marine resources to promote sustainable development” has received positive responses from countries around the world [88]. There are several projects currently sponsored by the National Natural Funds of China. Support from national laboratories in testing new devices may help greatly in demonstrating design concepts and reliability of new devices. As long as progress is being made in the development of artificial downwelling technologies, the increasing trend in government funding is likely to continue to rise. Technical and financial support from governments across the globe may be crucial in transforming new artificial downwelling technologies from prototypes to commercially viable products.

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