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Review

Green and Sustainable Biochar for Coastal Wetlands Management: A Review to Achieve In Situ Remediation by Artificial Intelligence

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Abstract: Coastal wetlands, often referred to as the 'kidneys of the Earth', have gained significant attention. However, they are increasingly affected by severe pollution and invasive species. Thus, ensuring green and sustainable methods for pollutant removal is of utmost importance. Biochar has demonstrated its unique advantages and benefits in coastal wetland remediation and management. In addition, the application of artificial intelligence (AI) in environmental fields has become increasingly prevalent, with the aim of improving the efficiency and effectiveness of environmental protection and resource management. However, the in situ remediation with AI-assisted biochar is still not well understood. This review adopts a problem-focused approach, analyzing and resolving problems to comprehensively review state-of-the-art biochar production, modification, and applications. This study aims to improve the remediation efficiency of sediment with combined pollution through the integration of AI systems. Moreover, the study highlights the positive effects of biochar on plant growth, microbial activity, and soil/sediment health, as well as its suitability for coastal wetland management, indicating that biochar holds great promise as an effective method for coastal wetland remediation and management.

Keywords: green and sustainable remediation; biochar; coastal wetland management; artificial intelligence

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1. Introduction

Coastal wetlands are terrestrial and marine staggered ecosystems of transition [1,2]. With the development of industry and the expansion of the population, the global demand for wetland ecosystems is continuously increasing due to their ecological benefits and high biomass productivity. They attract great attention because of their continuous exchange of essential nutrients (such as carbon, nitrogen, phosphorus, and potassium) and energy with the upstream rivers and the ocean under periodic tidal variation. Additionally, sediment organic matter is becoming rich via the slow rate of the tidal current, which accelerates the aggregation and circulation of contaminants [3,4]. These contaminants are toxic to all living beings (humans, animals, and plants), even at low concentrations [5].

Furthermore, it is important to note that coastal wetlands in China are currently facing a significant issue of biological invasion. In particular, the introduction of *Spartina alterniflora* (*S. alterniflora*) from the US Southeast Coast and the Gulf of Mexico to the southeastern coast of China in 1979 was intended to serve various purposes, such as wave dissipation, embankment protection, siltation promotion, and land reclamation [6].

However, due to its strong environmental adaptability, high tolerance to heavy metals, strong reproductive ability, and rapid growth, *S. alterniflora* has rapidly expanded and spread throughout China's coastal zone. Consequently, this invasive species has inflicted severe damage to the ecological structure of coastal wetlands, posing a serious threat to local biodiversity resources [7]. As summarized in Table 1, the area of S. alterniflora in nine coastal provinces was over 51,970 ha in 2020 [8–10] as it has almost no natural enemies. Among the coastal regions, Jiangsu province had occupied about 31–33% of the *S. alterniflora* total area (16,183 ha) [11]. Generally, in the late stages of *S. alterniflora* growth, the average biomass was 2657 $g\cdot m^{-2}$ (above-ground) and 3517 $g\cdot m^{-2}$ (below-ground) [10]. The total dry above-ground biomass can reach 7.5×10^5–1.15×10^6 $t\cdot a^{-1}$, which is equivalent to 4.4–6.7% of the yield of China's crops straw in 2014 [12]. Faced with such a huge biomass, how to effectively deal with the invasive species to achieve environmental sustainability has attracted the focus of researchers.

Table 1. The area and proportion (2015, 2018, and 2020) of *S. alterniflora* in coastal provinces of China (ha).

Province	2015		2018		2020	
	Area (ha)	Proportion (%)	Area (ha)	Proportion (%)	Area (ha)	Proportion (%)
Hebei	0	0	128	0.24	520	1.0
Tianjin	436	0.8	331	0.62	156	0.3
Shandong	2510	4.6	3567	6.69	6184	11.9
Jiangsu	18339	33.6	17490	32.8	16163	31.1
Shanghai	10097	18.5	9124	17.11	9095	17.5
Zhejiang	14354	26.3	12696	23.81	9355	18.0
Fujian	7259	13.3	7743	14.52	7847	15.1
Guangdong	764	1.4	1109	2.08	1299	2.5
Guangxi	818	1.5	1114	2.09	1299	2.5
Total	54,580	100	53,324	100	51,970	100

Note: Data source: [9,12].

The application potential of *S. alterniflora* and its economics function was summarized (Figure 1) [13–17]. Among them, biochar has received extensive attention. The large-scale application of carbon materials rapidly developed due to its cost-effective, carbon-rich, green, and sustainable properties, which are useful for the in situ remediation of contaminants. However, some physicochemical properties of biochar, such as surface functional groups, the specific surface area (SSA), and pore structures, can limit its capacity as an adsorbent. For example, pristine pyrolysis biochar often exhibits lower adsorption of contaminants in the soil/sediment than physicochemical modification biochar [18]. One way of improving the performance of biochar is to enhance the surface characteristics and alter/optimize the composition of the feedstocks [19].

The practical application of carbon materials has increased rapidly over the past two decades, resulting in an enormous number of published articles related to biochar (Figure 2A); however, few studies have been published regarding pollution remediation using coastal wetland invasive plant (*S. alterniflora* as an example) biochar, which is a strategy of 'treating the wastes with wastes' with no secondary pollution, ensuring the stable operation of coastal wetlands.

In recent years, the application of artificial intelligence (AI) in the environmental field has been increasingly prevalent, with significant potential in the remediation of coastal wetland pollution. Applying AI to coastal wetland protection enables us to effectively optimize resources while enhancing the efficiency and accuracy of environmental management [20]. For instance, AI technologies can assist in monitoring and predicting heavy metal pollution in coastal wetlands. Through big data analysis and machine learning algorithms, it is possible to rapidly and accurately identify the sources and levels of pollution. Utilizing intelligent control systems and robotics, the precise treatment and restoration of polluted soil and water bodies can be achieved, thus enhancing remediation efficiency and reducing costs. This provides a scientific basis and decision support for environmental protection agencies. Moreover, AI can aid in designing and optimizing remediation strategies to achieve the best possible restoration outcomes.

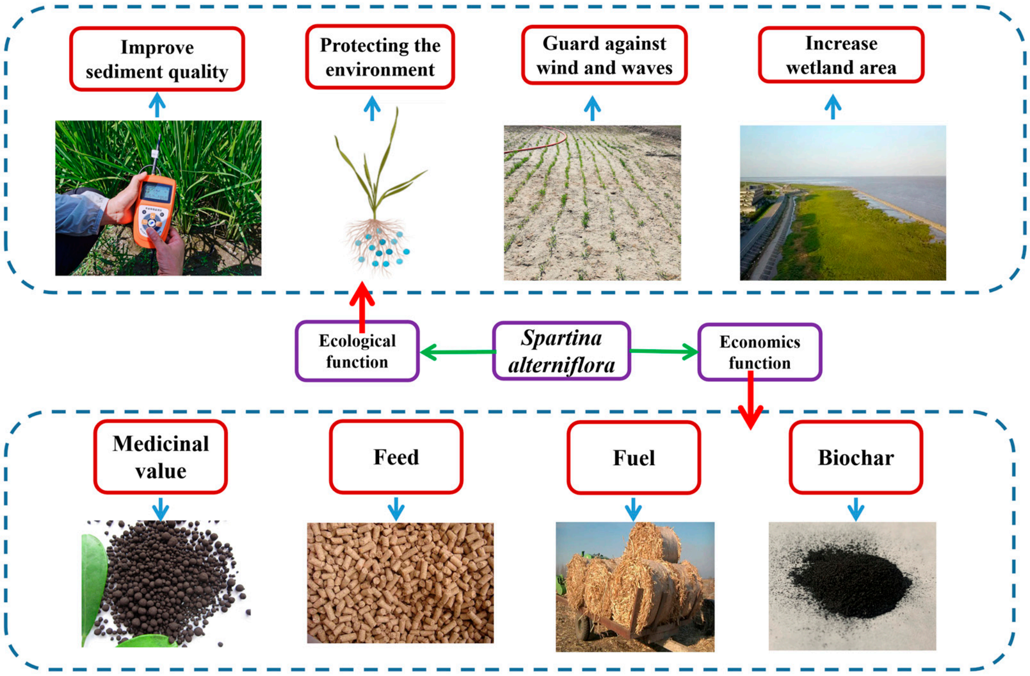

Figure 1. Coastal wetland plants (*S. alterniflora* as an example) have tremendous potential to be utilized as precursors for waste-to-resource conversion.

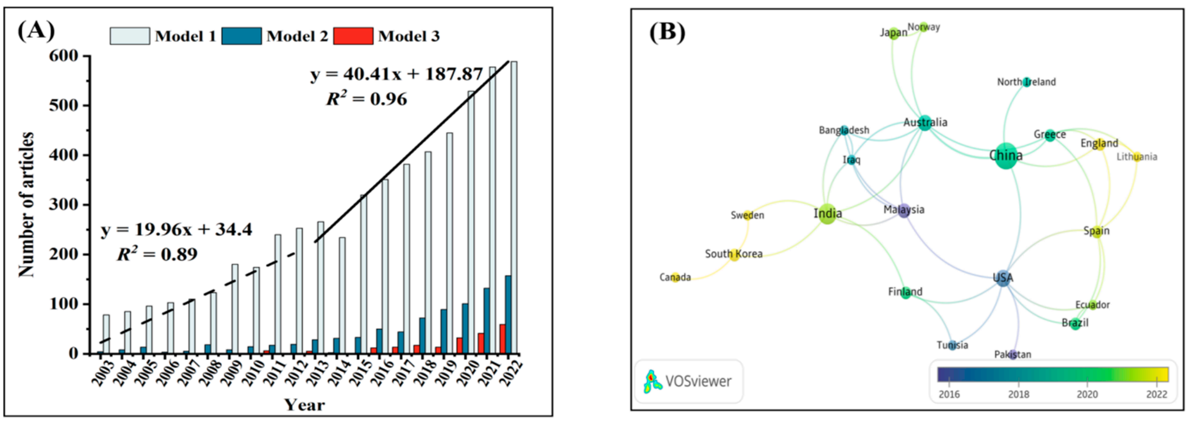

Figure 2. *Cont.*

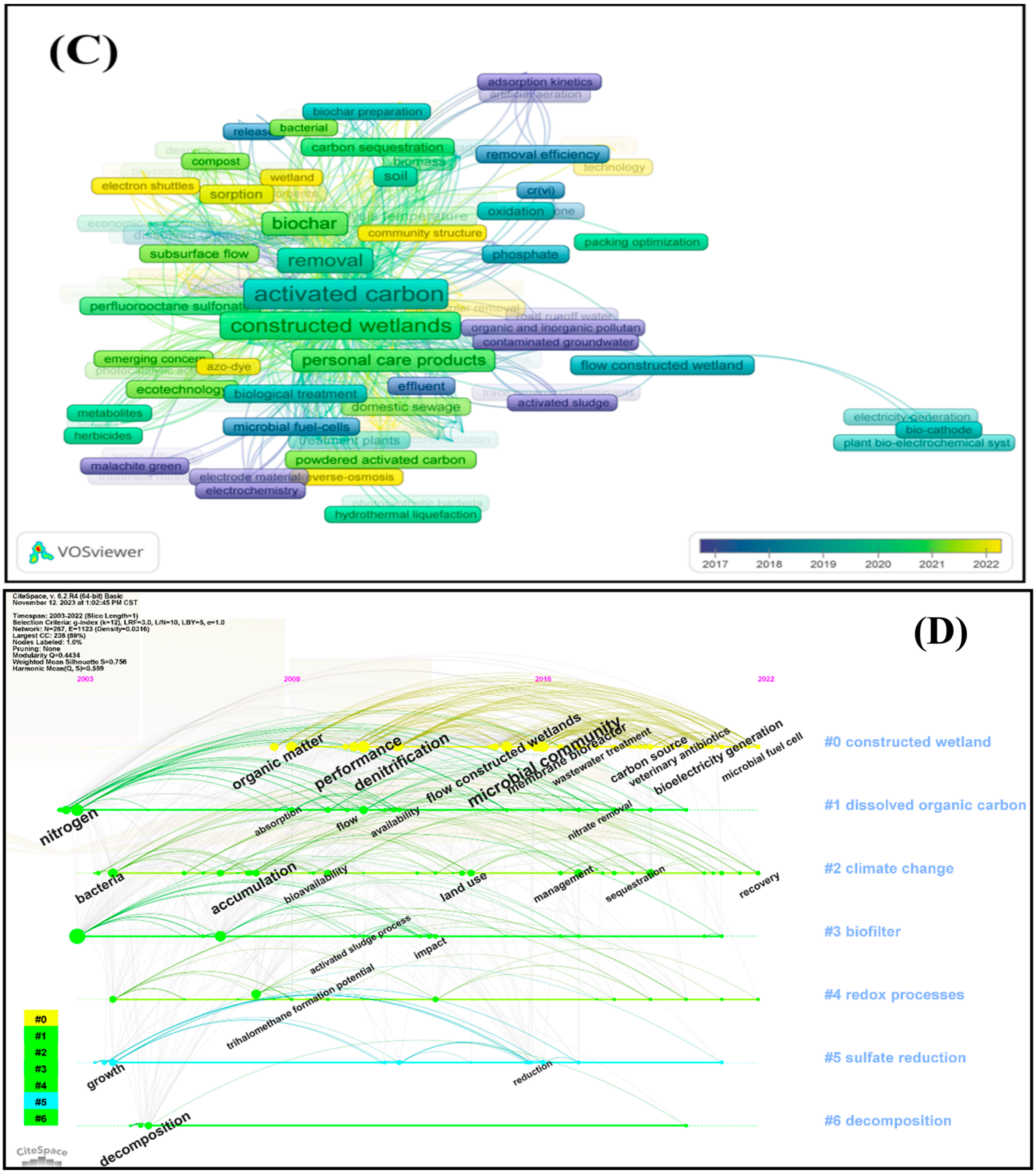

Figure 2. Three models analyzing publications and their trends analysis in the past 20 years (2003–2022). (**A**) The annual number of articles published on three different models during the 20 years. (**B**) The contribution and collaboration networks of major countries during the 20 years; each node represents a country. (**C**,**D**) were bibliometric networks of biochar application in coastal wetlands, analyzed using VOS-viewer and Cite-space, respectively. Each connected group of nodes shows collaborative relationships and the positive correlation between the node size and the number of articles. The color of coordinates in the lower right corner of (**C**) indicates the average number of articles per year in the country.

The usage of AI principles and deep learning (such as big data analysis and data mining) in the optimization of pristine and modified biochar represent the novel direction of the biochar field, predominantly exploited for how the thermodynamic and kinetic adsorption of contaminants were affected by the feedstock variables (such as phytochemical components and particle size) and preparation process (such as oxygen treatment, pyrolysis temperature, and combustion duration) [21]. Once these templates are gained, they can be selected, extended, and combined for the activation and functionalization of biochar to enable efficient adsorption for single-medium (such as aqueous phase, liquid phase, plants, and animals' system) as well as multi-component (such as the mixing system) effluents in coastal wetlands. However, there are not many similar studies about the high additional value of coastal wetland plant wastes. Thus, we focused on the following issues based on the information of the "big literature" era: (1) we illustrated the characteristics and development of coastal wetland plant biochar, (2) we discussed various preparation processes and modification methods, (3) we elucidated the importance of AI application in selecting biochar properties and optimizing the removal effect, (4) we explored the effects of biochar on plants and soil/sediments, verified its safety, and explored the application prospects of biochar in coastal wetland management. This review provides a valuable perspective, proposing the structuring of the green and sustainable management of coastal wetlands based on AI systems.

2. Data Collection and Trends Analysis in Publication

Research into plant waste and in situ remediation could trace back to the Amazonian study in the 1980s, referring to 'Terra Preta' agriculture [22,23]. Biochar has been widely used for improving soil fertilizers and agricultural productivity in observational and experimental studies. The bibliometric analysis could reflect the evolutionary trajectory of the scientific literature (such as research and review articles) on biochar research using the database of Web of Science [24]. The bibliometric analysis indicated that about 5543 articles have been retrieved from the Web of Science database, ranging from 1 January 2003 to 30 December 2022 on model 1 (Table S1) in coastal wetlands; among them, 846 were model 2 articles and 203 were model 3 articles. Based on model 1, there were significant increases in each decade (Figure 2A), which fitted well ($R^2 > 0.89$) with the linearity kinetic. In the first decade (2003–2012), the articles published showed an accumulation trend, and the second decade (2013–2022) exhibited a J-shaped (acceleration stage) trend, which was three times that of the accumulation stage.

After 2002, with respect to the articles published in the different countries, the publications in China and the US had higher rates, greater influences, and stronger international collaborations than other publication countries (Figure 2B). Then, the bibliometric network of biochar application in coastal wetlands was analyzed using VOS-viewer 1.6.19 (Leiden University, Netherlands) and Cite-space 6.2.R4 (Drexel University, PA, USA) (Figure 2C,D); keywords such as activated carbon, wetland, and contaminant environmental behaviors had the strongest collaborations. Terms like microbial community, phytoremediation, and treatment plants highlight the interaction between plants and microbials for the removal of contaminants. The sorption, desorption, biodegradation, and clogging process keywords suggest the significant mechanisms which may be involved in biochar application. The terms heavy metals, emerging contaminants, and PAHs mostly appeared regarding their removal by carbon materials (other keywords in Figure 2C). However, the study of combining AI and/or deep learning with coastal wetland management rarely appeared. Therefore, coastal wetland biochar can serve as an efficient managed and treated coastal wetland, owing to its enhanced contaminant adsorption potential and its reduced secondary pollution characteristics.

As Figure 2C reported, words such as economic assessment, policies, and ecotechnology, as important parts of remediation management, have been widely accepted in reducing secondary pollution globally. The most effective method of biochar sustainability capability and its possibility analysis was using life cycle assessment (LCA) and cost–benefit analysis (CBA), which were calculated to quantify and justify the carbon footprints and profit values of coastal wetland plant (*S. alterniflora* as an example) biochar, and to avoid CO_2 emissions, achieving economic benefits via energy efficiency trading [25]. In particular, climate change caused by global warming affects sea levels and coastal wetland ecosystems [26], with large quantities of CO_2 emissions becoming a common issue in some countries (such as China, Australia, and South Korea) from 1991 to 2021 (Figures S1 and S2). Biochar was recognized as a green and sustainable material for CO_2 sequestration, contributing to carbon neutrality, with a trap capacity up to 2.0–2.6 times of its own weight, according to the new Intergovernmental Panel on Climate Change report [27,28].

3. Factors Influencing Biochar in Coastal Wetland Management

3.1. Feedstock

Generally, biomass such as municipal solid wastes, sewage sludge, animal wastes, and plant waste can all be used as feedstock for biochar. Coastal wetland plants (such as mangrove plant, *S. alterniflora*, and *Phragmites australis*) often have more cellulose, lower O/C values (molar ratio), and greater stability when compared to agriculture and animal wastes (Table 2) [1,22]. Furthermore, the content of N in the wetland plant biochar was higher than that of terrestrial plants, suggesting its potential as a nitrogen-doped carbon functional compound material [29]. As shown in Table 2, biochar derived from plant sources exhibits the highest carbon content and the lowest ash content. This can be attributed to the abundance of lignin, cellulose, and hemicellulose, which are the primary sources of carbon formation [30].

Besides the inherent differences in terms of nutrient properties, biochar's yield from coastal wetland plants were high with metal contents in its surrounding environment, which changed the bond length and bond dissociation energy through a series of metal chelation processes [31]. Moreover, the metal particles may block the pore structure of biochar, causing the decreased levels of SSA and pore volume [32]. The volatile components in the feedstock may increase the yield, and the gaseous products were observed simultaneously [33]. Moreover, the biochar with a high ash and mineral content is more suitable for soil/sediment pollution remediation and soil/sediment nutrient supplementation.

Table 2. Physicochemical properties of biochar derived from different sources.

Feedstock	Production Conditions			Element (%)				Yield (%)	Ash (%)	Surface Area (m^2/g)	pH	References
	Temperature (°C)	Heating Rate (°C/min)	Duration Time (h)	C	H	O	N					
Biomass residue	500	10	2	22.92	1.09	-	2.17	-	-	-	9.91	[34]
Food waste	350	-	3	43.3	2.3	16.7	1.93	20	-	8.99	9.93	[35]
Food waste	800	5	1.67	53.28	1.47	19.44	2.46	54.20	20.21	462.83	-	[36]
Mangrove	600	35	4	52.44	0.41	-	0.97	-	-	6.11	6.68	[37]
Spartina alterniflora	500	10	2	54.45	2.35	11.75	0.43	30.09	31	24.85	9.2	[38]
Phragmites australis	600	5	2	50.39	1.93	8.98	2.46	40.52	36.24	-	9.58	[22]
Nelumbo nucifera	600	10	2.5	73.79	1.96	12.76	1.47	38.07	9.78	24.15	-	[39]
Miscanthus	450	50	-	68.4	4.7	20.1	0.6	-	6.1	0.27	7.2	[40]
Arundo donax L.	600	-	2	77.10	2.16	11.97	0.79	30.5	10.75	50.05	10.41	[41]
Rice husk	500	5	2	52.78	2.07	11.2	0.07	37.90	-	257.5	9.3	[12]
Rapeseed stem	450	5	1	73.46	3.03	12.19	1.09	-	8.22	37.3	-	[42]
Poultry manure	450	-	3	33.4	-	-	2.53	-	58.2	-	9.32	[43]
Cow manure	550	15	1	49.91	1.82	13.16	2.11	38	33.0	-	12	[44]
Human manure	600	15	0.67	37.9	1.8	56.4	2.9	31.2	10.7	-	10.7	[45]
Rabbit Manure	300	3	1	31.3	3.3	12.1	2.1	-	50.6	-	8.6	[46]

3.2. Pyrolysis

Plant wastes can be converted into high-value treasures (biochar) via pyrolysis treatment under hypoxic or anoxic conditions [19,47]. Based on the heating rate, time, and temperature, pyrolysis can be divided into fast pyrolysis and slow pyrolysis. Fast pyrolysis involves high temperatures (such as 400–900 °C), in which the vapor residence time is usually 2 s, and then the high yields of by-product (gaseous and bio-oil) and carbon-rich substances are produced [48]. Slow pyrolysis involves low heating rates (such as 0.1–1 °C/s), suitable temperatures (such as 200–600 °C), and a relatively long vapor residence time (such as >0.5 h), which is the primary route for producing biochar, and includes three steps as follows: (1) dehydration reaction (such as <200 °C), where the water is dissipated; (2) thermal cracking and thermal degradation (such as 200–400 °C), which is the stage of biomass rapid loss, where the chemical bonds start to break and some substances start to volatilize; and (3) volatile carbonization (such as 400–600 °C), where the remaining ash and volatile substances are removed [49].

Pyrolysis conditions, such as the pyrolysis temperature, heating method, and residence time, are the key factors of biochar properties. Generally, the carbon content, aromaticity, and by-products of biochar increased, the adsorption capacity will be enhanced, while the H, O, N, and S content decreased with the increasing pyrolysis temperature. The higher the temperature, the larger the SSA and porosity of the biochar will be [50]. However, there are also reports that pyrolysis temperatures which are too high can cause the pore walls of the biochar to collapse or sinter, leading to increasing levels of micropores, and decreasing its average pore sizes, functional groups, and the cation exchange capacity of biochar [42]. With the increases in pyrolysis temperature, cellulose and hemicellulose decompose, unstable substances volatilize, and the yield decreased; meanwhile, the ash containing alkaline minerals increased and the pH values increased [51].

The heating method also effects the biochar's properties, for example, biochar produced by high-temperature usually with high surface areas and porosity, and prepared by hydrothermal carbonization have greater hydrophilicity and more surface functional groups [48]. In addition, the faster the rate of temperature increases, the larger the pore sizes, the lower the yields and aromaticity of biochar. The longer the residence times, the higher microporous volumes and the more total pore volumes of the biochar, and the content of fixed carbon also increases correspondingly [52].

3.3. Impact of Biochar Modification on Enhancing Contaminant Removal Efficiency

The effectiveness of biochar in soil pollution remediation is important, and the traditional activation and engineering techniques for biochar enhancement are not able to meet the current requirements. As shown in Figure 3, biochar modification offers significant advantages and potential for pollutant removal, and the modifications with biochar engineering are discussed below.

3.3.1. Physical Modification

Ball milling helps to enhance biochar's surface complex, improve the cation–π interaction, and generate functional groups [53], which relates to large scale environmental remediation [54]. Similarly, microwaves and ultrasonication are observed to promote the dispersion and breakup of nano-particles on the biochar surface and improve the porosity without clogging [55,56], which are often used to assist in chemical modification. Gas activation increases biochar's surface area and micropores, which can make it more suited to the removal of contaminants. With the increased reacting gasses and times, the pore sizes of products in heavy metal adsorption becomes more important [57]. As Zhang et al. [58] reported, ammonia gas modification in biochar resulted in increased N-functional groups.

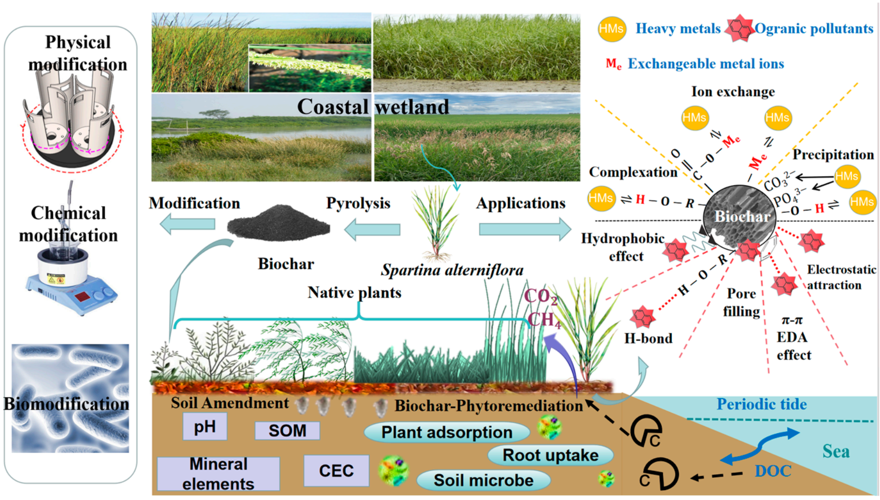

Figure 3. The application of biochar's effect on biochar-amended sediment based on the pot and field experiments.

The particles of biochar are small and can easily block the sieve, making it difficult to recycle and reuse. Impregnating the iron ions into the biochar is an approach to solving this problem, which can separate biochar from the solution with an external magnetic source, leading to decreased recycling costs and satisfying biochar sustainability simultaneously. Furthermore, magnetic modification also improves the adsorption capacity of phosphates [59] and heavy metals (such as Cd, Cu, and Cr) [60,61]. However, it has the disadvantage of causing secondary pollution because of iron leaching [19], leading to the magnetic property of Fe biochar being reduced; the biochar cannot be further utilized [62,63]. These physical activations are relatively simple; the requirements of high efficiency prompted scientists to expand other chemical activation technologies (such as acid, alkaline, and metals treatment).

3.3.2. Chemical Modification

There are two methods for the chemical modification of biochar as follows: modifying the feedstock before pyrolysis to produce biochar, or producing biochar first and then conducting chemical modification. The feedstocks are impregnated with the chemical agent, and then pyrolysis occurs at various temperatures under the N_2-filled or inert atmosphere.

The current used for chemical modifications comprises low molecular weight organic acid (such as arginine, acetic acid, and citric acid), hydrochloric (HCl), phosphoric acid (H_3PO_4), and nitric acid (HNO_3) [19,64]. The type of functional groups varies with the different acid solutions; H_3PO_4 modification led to P-containing functional groups (such as P-O and P-C) with higher O/C ratios, which can inhibit the organic component's decomposition [65]. Arginine is bound to biochar's surface via H-bonding and van der Waals forces; the high N content and oxygen-containing functional groups (OFGs), such as -OH, R-O-R, -CHO, -C=O-, -COOH, and -COOR, are sufficient for adsorbing contaminants [66,67].

With the alkali modification, organic components and ash normally dissolved in biochar, increasing the O/C ratio and hydrophobicity [68]. The -C=O bonds on biochar's surface were increased based on the increase in the positive charges, leading to the sorption capacity of negatively charged ions being promoted [69].

Oxidant modification decreases the sorption capacity of biochar because the OFGs' oxidant effect was increased (such as H_2O_2 and $KMnO_4$) [70]. If the content of H_2O_2 exceeds 10%, it is beneficial for dispersing π–π bond's interaction. As the literature reported by [71] shows, the impregnation of H_2O_2 contributed to increasing the OFGs on biochar's surface and to enhancing the effective adsorption of methylene blue.

3.3.3. Biomodification

Biomodification involved the inoculation of specific microorganisms on biochar's surface, forming biofilms to enhance its adsorption capacity. The pyrolysis of the waste from anaerobic digestion produces biochar [72,73] and enhances the ability of biochar to remove contaminants.

4. Exploration the Role of Coastal Wetland-Biochar Application on Sediment Contaminants Behavior

The contamination of coastal wetlands is severe due to the continuous exchange of substances and energy both upstream and downstream and the abuse of pesticides and fertilizers in agriculture. Biochar gradually but significantly removes the pollutants in the coastal ecosystem through its highly efficient, green, and sustainable properties, which are attributable to the concomitance of various adsorption mechanisms. The efficient removal of contaminants by biochar from the coastal wetlands is a popular area in recent years; here, the remediation of heavy metals and organic contaminants is discussed due to their toxicity and density (metals' density is up to 4.0 g cm^{-3}) [74,75].

4.1. Heavy Metals

The mechanisms of biochar removing heavy metals has been widely reported, including cation exchange, co-precipitation, complexation, and surface and pore medium adsorption. Surface adsorption is one of the most significant mechanisms for biochar-based materials; for example, the adsorption capacity of Cd^{2+} in invasive plant (*Eichhornia crassipes*) biochar increased from 49.5 to 70.31 mg g^{-1} when pyrolyzed at 250 and 450 °C, respectively [76], due to the ability of surface complexation/sorption having increased with the increasing temperatures of the biochar. The absorption isotherms of Cd^{2+} with *S. alterniflora* biochar has shown that the adsorption capacities were positively correlated with the surface areas and porosity conditions ($p < 0.05$),were driven by the diffusion from biochar's surface to micropores and the interior [77], and that its adsorption capacities (16.29–32.34 mg g^{-1}) were higher than reed (0.42–0.88 mg g^{-1}) [78] and *miscanthus* (9.21–11.5 mg g^{-1}) [79], but lower than *Phragmites australis* biochar (30.98 mg g^{-1}) [80] and marine macro algae (37.2–60.7 mg g^{-1}) [81].

It is well established that electrostatic interactions were involved in the adsorption process, that the soil's CEC was increased along with the biochar addition, and that this caused heavy metals to be firmly adsorbed in soil/sediment biochar systems, reducing their mobility. As listed in Table 3, even if there are other mechanisms influencing the adsorption behaviors, the heavy metal adsorption on biochar was mainly affected by the precipitation/coprecipitation interaction. For instance, *S. alterniflora* biochar sequestered Cd^{2+} in soil via co-precipitation with silicon and aluminum (silicon–aluminum–Cd complexes) [82]. *Phragmites australis* biochar can provide plenty of binding sites to adsorb heavy metals (such as Cd, Cr, Cu, Pb, and Zn) based on Fenton oxidation and other oxidation reactions [83]. In addition, as the pyrolysis temperatures increased from 300 to 700 °C, the biochar's OFGs (such as -OH, -COH, and -COOH) increased, leading to the decrease in negatively charged on the biochar's surface and the increase in sorption capabilities [84].

Table 3. The removal capacity of various contaminants on biochar in recent studies.

Contaminants		**Biochar Types**		**Experiment Conditions**		**Elemental Composition %**				**Removal Efficiency**	**Removal/Adsorption-Mechanisms**	**Reference**
Type	**Species**	**Feedstock**	**Tp (°C)**	**Sorbent Dosage**	**Concentration**	**C**	**N**	**H**	**O**			
Inorganic	Cd^{2+}	*Spartina alterniflora*	350 450 550 650	1, 5 and 10%	2.73 mg·kg^{-1}	65.51 69.80 70.71 71.18	0.81 0.88 0.72 0.66	4.14 3.07 2.19 1.34	15.17 10.37 5.59 6.51	26.9% - - -	Physical adsorption and Cd reaction with certain organic functional groups	[16]
Inorganic	Cd^{2+}	*Spartina alterniflora*	450	0–0.1 g	0–50 mg L^{-1}	69.80	0.88	3.07	10.47	16.29–32.34 mg kg^{-1}	Precipitation and Van der Waals force	[77]
Inorganic	Cu^{2+}	*Reed* *Gladiolus*	600 600	1.2 g 1.2 g	10–200 mg·kg^{-1}	- -	- -	- -	- -	>50% >50%	Physical adsorption, ion exchange, electrostatic adsorption, surface complexation, and precipitation	[85]
Inorganic	$Cu^{2+}$and Pb^{2+}	*Phragmites australis* *Suaeda salsa* *Tamarix chinensis*	500 500 500	0–2% 0–2% 0–2%	200 mg L^{-1} Pb^{2+}, 5 mg L^{-1} Cu^{2+}	43.51 58.04 36.17	10.23 0.92 7.05	- - -	46.26 35.04 56.78	82.15% 84.94% >90%, >90% 61.74% 96.19%	Oxygen-containing functional groups and a large number of cations (Ca^{2+}, K^{+})	[84]
Inorganic	Cd^{2+}	*Spartina alterniflora*	450	0–10%	3 mg·kg^{-1}	84.67	0.10	3.52	-	-	Precipitation/coprecipitation and specific chemisorption	[82]
Inorganic	Cd, Cr, Cu, Pb, and Zn	*Reed*	800	-	mix	-	-	-	-	-	Oxygen-containing functional groups and electrostatic attraction	[83]
Inorganic	Cd^{2+}	*Vetiver grass*	400	20 mg	0–320 mg L^{-1}	62.06	1.29	2.01	15.24	33.1 mg g^{-1}	Electrostatic adsorption, surface complexation, and precipitation	[86]
Organic	Malachite green	*Spartina alterniflora*	800	40 mg	400 mg L^{-1}	-	-	-	-	98.38%	A large number of hydroxyl functional groups on the biochar surface	[87]
Organic	Diclofenac	*Reed*	-	-	0.05 mg L^{-1}	-	-	-	-	95%	Physical adsorption and oxygen–functional group binding	[88]
Organic	Prfluoroalkyl acid	*Phragmites australis*	500 700 900	2 mg 2 mg 2 mg	100–250,000 µg L^{-1}	- - -	- - -	- - -	- - -	- - >80%	Physical adsorption, hydrophobic adsorption	[89]
Organic	PAHs	*Mangrove plant*	400 600	2 mg 2 mg	0.5–16 mg L^{-1}	43.26 52.44	1.34 0.97	0.54 0.41	 -	39.21 mg g^{-1} 42.23 mg g^{-1}	Physical adsorption, hydrophobic adsorption	[37]
Organic	PAHs	*Arundo donax/* CuO	500	40%	-	75.04	1.89	-	22.28	94.09%	Complex absorption, hydrophobic adsorption, and electrostatic attraction	[90]
Organic	Chlorpyrifos and chlorpyrifos-methyl	*Reed*	300	0.5–1 mg	0–1 mgL^{-1} Chlorpyrifos, 0–4 mg L^{-1} chlorpyrifos -methyl	65.26	0.64	4.51	21.03	Optimal removal 21.8 mg g^{-1} 50.50 mg g^{-1}	Hydrophobic interaction and π–π interaction	[91]

4.2. Organic Contaminants

Generally, the removal efficiency of organic contaminants by biochar is higher than that of heavy metals due to their larger SSA and electron-rich groups that can act as electron donors to interact with biochar [22]. Current studies reported that the mangrove plant biochar produced at high temperatures (600 °C) exhibited larger sorption efficiency (42.23 mg g^{-1}) for PAHs [37,92], which is higher than mangrove plant biochar, which was pyrolyzed at 400 °C (39.21 mg g^{-1}), and *Arundo donax* biochar loaded with copper (12.04 mg kg^{-1}) [90]. Mangrove plant biochar interacted with PAHs via physical adsorption (larger SSA) and hydrophobic adsorption. Surface complexation, electrostatic attraction, and hydrophobic adsorption are involved in *Arundo donax* biochar, and its mechanism was different to mangrove plant biochar due to the discrepancy in feedstocks. Moreover, the π–π interaction [91] and binding with OFGs [88] are vital mechanisms in the removal of organic contaminants (chlorpyrifos/chlorpyrifos-methyl and diclofenac) by reed biochar.

As for green and sustainable remediation, the focus was mainly on biochar collaborating with soil/sediment microorganisms to degrade organic contaminates, which not only can improve the removal efficiency, but also accelerate soil/sediment fertility cycles and promote soil/sediment microbial activities. Yang et al. [93] found that biochar addition had a significant affect on the growth of wetland plants (such as *Typha latifolia* and *S. alterniflora*) and increased rhizosphere microbial activity after 2-year experiments. The high level of removal of PAHs was proven following the application of mangrove plant biochar, while the degradation ability sharply decreased after the addition of sodium-azide in the same system; therefore, microorganism degradation plays a key role in PAH degradation [37,92]. Among PAHs, when compared with four-ring PAHs (pyrene), three-ring PAHs (phenanthrene) had a lower resistance to biodegradation [64,94].

5. AI Usage in Coastal Wetlands Management

Although biochar displays the efficient immobilization and adsorption of inorganic and organic contaminants in water–sediment systems, how to deal with the parameters and processes regarding obtaining the optimal removal capacity has attracted researchers' attention. The rapid development of AI is constantly being applied in environmental governance. Moreover, the application of AI in coastal wetland pollution remediation can improve efficiency, reduce costs, and bring more precise and sustainable remediation effects. The frame diagram (Figure 4) followed the process of "find problems—analyze problems—resolve problems", thus combining AI and deep learning into the production or application of biochar. The process starts from determining the water–sediment parameters (find problems), → followed by biochar production and the analysis of its yield from different pyrolysis processes, → then characterize the changes in the properties based on biochar modification (analyze problems), → utilize the biochar for coastal wetland remediation (resolve problems), → recycle and reuse biochar [19].

Specifically, this process establishes an objective/plan (such as the remediation of coastal wetlands or improving sediment quality), which was used to analyze the problems and select different mechanisms of biochar that fit this objective. When biochar is applied to remediate coastal wetlands, firstly, to determine the types and concentrations of polluted sediment (such as inorganic or/and organic contaminants), the "fluorescence fingerprint" is simultaneously used to obtain water–sediment parameter information [95,96]. Or, when applied to improve the quality of sediment, the algorithm starts from investigating the sediment properties (such as organic matter, pH, microbial communities, and nutrient composition). Then, the water–sediment parameters are managed by deep learning algorithms, such as random forest and support vector regression, to make decisions when meeting one or several certain standards.

Subsequently, biochar is produced based on the coastal wetland plants (native plant wastes/invasive plant (refer to Sections 3.1 and 3.2)), and characterizes the SSA, functional groups, porosity, and other physicochemical properties (such as elemental compositions and pH) to generate databases, which are also obtained with deep learning toolboxes, such as the average percent relative error (APRE, %), root mean square error (RMSE, R^2), and average absolute percent relative error (AAPRE, %), as inputs matching the requirements during the decision-making stage, and changes the variables to a target table by applying weights [21]. Details of prediction and classification algorithms provide tremendous help in selecting biochar with optimized properties, which can be found in the prediction experiments/models and other relevant studies [21].

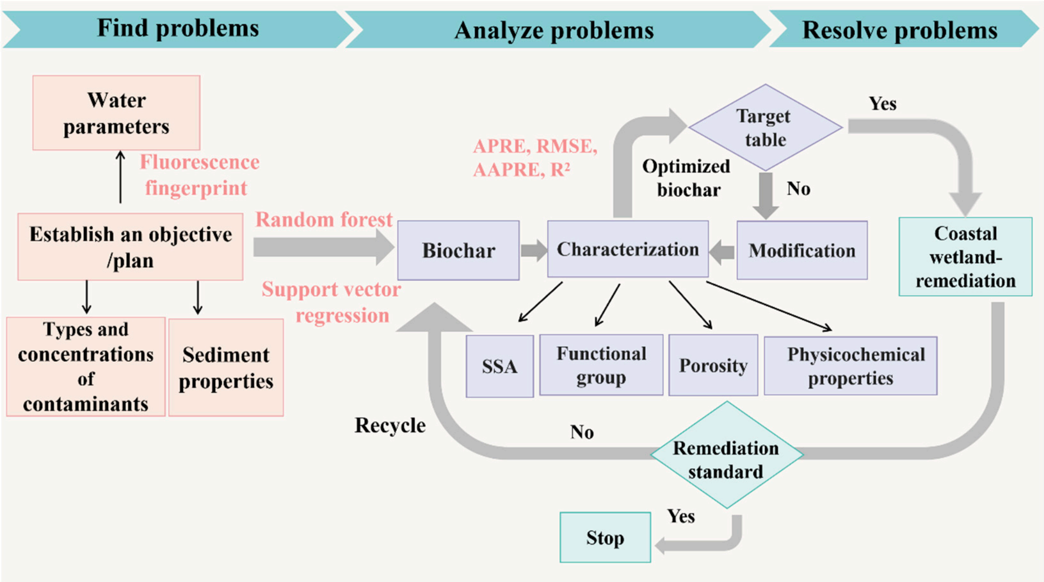

Figure 4. Process diagram of incorporating artificial intelligence into biochar coastal wetland remediation systems.

The target table is applied as a standard to select biochar based on whether it matches the purpose of remediation. If the requirements can be met, biochar would be used for coastal wetland remediation (refer to Section 4); otherwise, it will need to be activated by physicochemical modification (refer to Section 3.3). The modified/activated biochars are re-characterized and re-matched to the requirements by the deep learning algorithm to determine if the functionalized biochar can reach the coastal wetland remediation standards. This cycle is repeated again with selected properties until it passes the standards for coastal wetland remediation. Finally, an evaluation is conducted to ensure the sustainability capability of AI systems (refer to Section 6), and the fully utilized biochar can be recycled and reused several times [97,98].

In future, when combining simulated experiments, the processing efficiency of computers and real-time monitoring systems were established to assess the effects of modified/activated biochar on coastal wetland remediation, adjusting the remediation strategies to suit the practice conditions [19]. Furthermore, scientists can establish the multi-system and multi-module to decide which biochar is needed, then establishing indexes for modelling; therefore, when this proposed algorithm is fully developed, it also promotes AI and machine learning into environmental ecological remediation. Of course, this remediation model requires multi-domain integration among scientists in different fields (such as chemistry, materials, environmental, and software development).

6. Exploring the Role of Biochar on Plants and Soil/Sediment, and Verifying its Safety in the Management of Coastal Wetlands

The developed porosity of *S. alterniflora* biochar will provide the habitat space for the growth of microbes, promote its metabolism and biodiversity [99], and enhance the community height [17] in coastal wetlands. In the presence of invasive plant (*Eupatorium adenophorum*) biochar mixed with cow urine, the yield of pumpkin was significantly increased [100]. The effects of combined applications including *S. alterniflora* biochar and

Brassica chinensis (*B. chinensis*) in Cd-sediment were studied [82]; this is a biochar-assisted phytoremediation in the model soil (kaolin), and the bio-concentration factor values in *B. chinensis* were 24–31% after *S. alterniflora* application compared to the control plants, indicating that the Cd transfer from *B. chinensis* roots to aboveground parts was obviously attenuated, thereby reducing the inhibitory effect of Cd on *B. chinensis* growth. Adding *S. alterniflora* and water hyacinth biochar into soil as a remediation material can promote Cu^{2+} immobilization and promote the aggregation of soil particles (Ca) for soil amelioration [101].

In addition, research also revealed that phenanthrene and pyrene are accumulated mainly in plant roots with the addition of coastal wetland plant (*Kandelia obovate*) biochar [37], significantly reducing the risk of wetland exposure to harmful substances. Coastal wetland plants have evolved a series of self-protection measures to enhance their tolerances under pollution stress over a long time [90,99,102], such as increased physiological and metabolic activities, promoting the precipitation and chelation of metals in root cell walls and vacuoles [6]. When *S. alterniflora* grows under Cd stress, Cd was first adsorbed in the root cell wall, and then enters into the protoplasts, forming a complex with phytochelatin and thereby promoting its tolerance to Cd [6]. When compared with treatments involving no biochar, coastal wetland plant (*Kandelia obovate*) biochar application significantly decreased the activities of four antioxidant enzymes in *Kandelia obovate* roots, also showing obvious effects in phosphatidylserine secretion and cytochrome C release [1].

It is noteworthy that biochar application in coastal wetlands is a promising area in the foreseeable future. Biochar can reduce contaminant migration from the sediment to the plant in coastal wetlands, and the eco-physiological responses of plants to pollution stresses was improved correspondingly (Figure 3), which verifies its role in supporting coastal wetland security. Finally, the current reports are based on biochar-synthetized materials for laboratory experiments, while the applications focusing on the real environment are scarce; therefore, the combination of AI with in situ remediation in the field requires further investigation, which will further reveal its potential value.

7. Conclusions and Exploration the Future Efforts of Biochar on Coastal Wetland Management

Recently, the research hotspots of coastal wetlands has evolved over the past 20 years based on the information of the "big literature" era, and the number of related studies has increased significantly. However, the artificial intelligence (AI)-assisted in situ remediation including coastal wetland plant biochar process is still unclear. Coastal wetland biochar can serve as an efficient managed and treated coastal wetland because of its enhanced contaminant-adsorption potential and reduced secondary pollution characteristics. In particular, coastal wetland plant biochar exhibited higher yields and more nutrients when compared with agricultural and animal wastes due to its high content of cellulose and the abundance of elements. Here, following the process of "find problems—analyze problems—resolve problems", we combined the production, modification, and application of biochar using AI assistance to improve the remediation efficiency. In addition, it was found that biochar can reduce the migration of pollutants from sediment to plants in coastal wetlands, improve the resistance of plants to pollution stress, and verify its supporting role in the safety of coastal wetlands. We have also confirmed the safety of the use of biochar on coastal wetland plants and soil/sediment. The security of biochar on the coastal wetlands plants and soil/sediment was proven.

Coastal wetlands act as the sink of contaminants, and wetland plants have accumulated higher content of contaminants and moisture in comparison with agricultural wastes, which require additional costs and energies to evaluate the preliminary toxicity and pre-treatment processes. For instance, if the precursors contain higher water content, the derived biochars require pre-drying and grinding prior to transport and pyrolysis. Moreover, the sustainable supplying and transporting of coastal wetland plants could be a barrier due to its seasonal variation and periodic tidal changes; it is impossible to collect the feedstock at certain times of the year, and therefore a reasonable plan is needed to formulate large-scaled industrial biochar production. Notably, the multistage utilization system (via by-product separation and collection and multiple utilizations of biochar) can result in extra profit for the local farmers. In addition, the effect of charge-assisted hydrogen bonding (CAHB) between the biochar and contaminants has not been reported. The surface functional groups (O- or N-) of biochar are similar to the p*Ka* of organic contaminants (p*Ka* < 0.5), which affect the sorption capacity of contaminants; thus, the microstructure of biochar is needed to further research environmental applications.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16141966/s1, Figure S1: CO_2 emission for different countries/continents over the past 30 years; Figure S2. (A) The total CO_2 emissions in the world and China, (B) Partial data of energy consumption in China from 1991 to 2021, (C) Trends of the total energy consumption and its composition among all energy parts in recent 20 years, solid- lines represents the world and dashed-lines represents China. Table S1: Search items involved with three models to obtain various topics in coastal wetlands.

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