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REVIEW

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Frontier review of key reduction technologies and resource utilization of waste during the seaweed gel production process

Xianze Luo[1], Yanyan Wu[1], Shuhe Wang[1], Zhu Xiong[1], Xiping Du[1,2,3], Mingjing Zheng[1,2,3], Yanbing Zhu[1,2,3], Zedong Jiang[1,2,3], Qingbiao Li[1,2,3], Hui Ni[1,2,3,4], Zhipeng Li[1,2,3*] and Zhaohua Chen[1,2,3*]

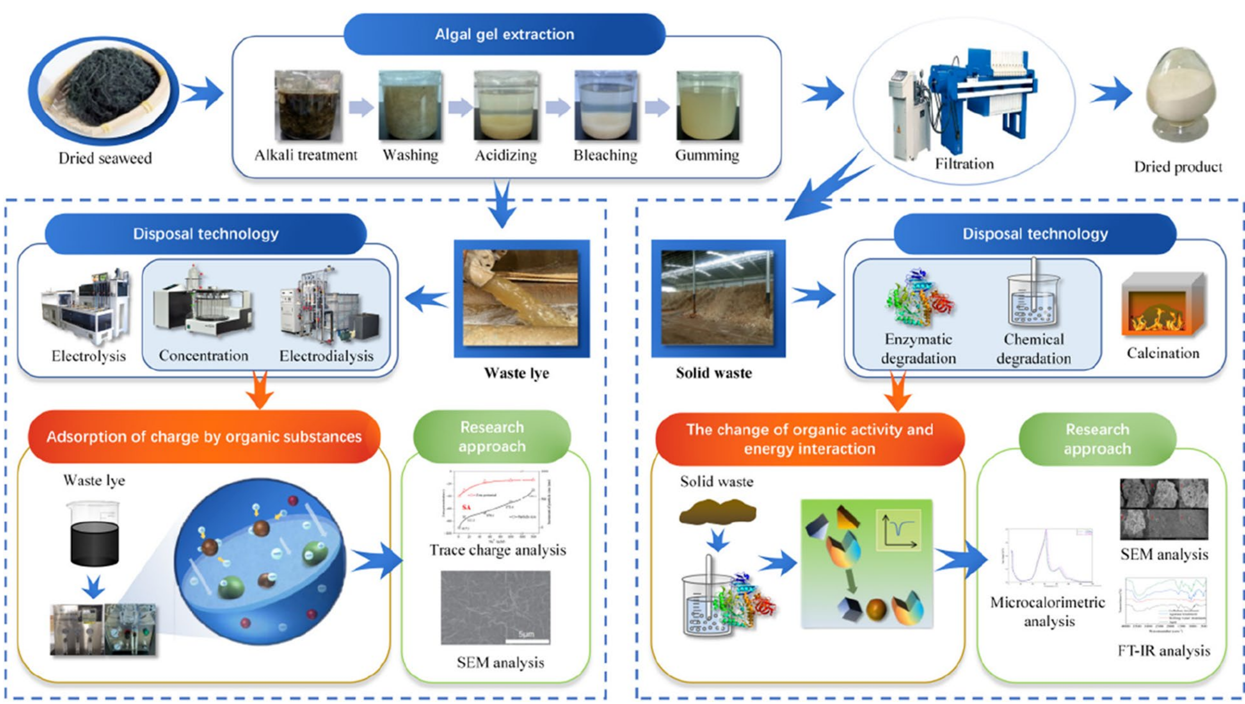
Abstract

In the production of seaweed gel (agar and carrageenan), significant amounts of waste lye and solid waste residue are generated, which contain a high concentration of organic components and perlite. The utilization rate of seaweed is low, and improper disposal of these wastes can lead to environmental pollution. Traditional waste treatment methods, such as neutralization, electrolysis, and calcination, consume large amounts of energy and are often ineffective in recovering organic substances and perlite efficiently. Emerging technologies, including electrodialysis combined with membrane concentration and the integration of enzymatic and chemical methods, offer promising approaches for the effective recycling and reuse of organic materials. However, the efficiency of recycling waste lye and waste residue is influenced by the charge release mechanisms during electrodialysis and the specific actions of enzymes. To further investigate the charge release mechanisms in the electrodialysis process for waste lye recovery, techniques such as trace-charge analysis, charge diffusion modeling, and scanning electron microscopy (SEM) may be employed. Additionally, microcalorimetry and thermodynamic models can be utilized to examine the energy changes of organic substances when subjected to specific enzymes during waste residue treatment. This study reviews the current state of waste treatment methodologies and corresponding technologies in the production of seaweed gel, providing a feasible research framework. It aims to establish a theoretical and technical foundation for reducing emissions of waste lye and residue while enhancing the efficient utilization of seaweed resources.

Keywords Seaweed gel, Waste lye, Waste residue, Treatment technologies, Recycle

*Correspondence:
Zhipeng Li
lzp2019@jmu.edu.cn
Zhaohua Chen
zhchen@jmu.edu.cn
Full list of author information is available at the end of the article

Graphic Abstract



Introduction

Seaweed is a multifunctional organism that produces a variety of polysaccharides (sulfated and nonsulfated) in the form of lamellar colloids, collagen, fucoidan, alginate, carrageenan or agar [1–4]. These polysaccharides are widely utilized in the development of biopolymers [5]. The commercial value of seaweed is primarily determined by its agar content and gel quality [6]. Seaweed gel, a colloid derived from seaweed, finds extensive application in food processing, biology, and medicine. Its quality is influenced not only by the species of seaweed and its geographical location [7, 8] but also by the storage and processing methods employed after harvesting. Red algae are particularly rich in agar [9]. Gracilaria, a significant species of red algae, contains approximately 30% agar and serves as the most important raw material for agar extraction, accounting for about 53% of the market demand [10]. At present, China and Indonesia are the largest producers and manufacturers of seaweed gel, achieved through both domestic and overseas cultivation [11].

The supply of raw materials for seaweed gel primarily originates from Indonesia, the Philippines, Chile, China, Peru, and other countries. Among these, Indonesia, the Philippines, Chile, and Peru produced a total of 418,700 tons in 2021. The methods of seaweed harvesting vary across countries due to influences from climate and hydrology. Chile and Peru predominantly rely on the collection of wild algae from the ocean, whereas Indonesia, the Philippines, and China mainly depend on aquaculture [12]. Wild seaweed typically flourishes in tropical waters near the equator. Frequent natural disasters, such as typhoons and earthquakes, result in a decline in the availability of wild seaweed, which significantly impacts the supply of raw materials for the entire seaweed gel industry. With advancements in aquaculture technology, an increasing number of countries are beginning to engage in seaweed farming. According to the Statistical Yearbook of World Food and Agriculture 2023 [13], global fisheries and aquaculture production reached 218 million tons in 2021, driven by the growth of aquaculture, particularly in Asia. Approximately 36.3 million tons of this total consists of algae, with 97% being cultivated.

As a primary producer in the ocean ecosystem, seaweed serves as a fundamental source of materials and energy. Its value significantly surpasses that of terrestrial crops, which is a key factor in promoting the development of the "blue industry" [14]. According to data from the China Fisheries Statistical Yearbook 2023 [15], seaweed cultivation in China has consistently increased from 2013 to 2022. By 2022, the total seaweed production in China reached 2.7239 million tons, with mariculture accounting for 2.7139 million tons. The national area dedicated to algae mariculture is projected to reach 139.48 thousand hectares, representing 6.72% of the country's total area. Shandong and Fujian provinces are the two most significant bases for seaweed industry development in China [16]. Fujian Province stands as the largest seaweed-producing area, yielding 1,301,000 tons of cultivated seaweed in 2022, which constitutes 47.96% of the total output. In the same year, the annual production of seaweed gel in Fujian Province was 10,900 tons, accounting for 60.36% of the national total. With the ongoing development of the seaweed glue industry, Fujian Province has emerged as the leading region in China's seaweed processing sector.

Currently, the primary extraction method for seaweed gum is the alkali process. however, this method generates a significant amount of waste lye and solid waste. As shown in Table 1, the annual output of waste generated from seaweed glue processing has exhibited a downward trend over the past five years, according to data from the China Fishery Statistical Yearbook. Nevertheless, the lowest production level of this waste still reaches 7,973,170 tons per year. The disposal of these wastes poses environmental burdens and leads to resource wastage. Recovering the active components from waste lye and solid waste is a crucial measure for the efficient utilization of seaweed resources. To optimize the recovery of waste lye and residue, it is essential to fully understand the internal mechanisms governing recovery speed and rate, as well as the changes in organic activity during the recovery process. Consequently, we plan to review the current status of waste treatment and related processing technologies. We will analyze the advantages and key scientific challenges of electrodialysis combined with membrane concentration, as well as the integration of enzymatic and chemical methods in waste treatment processes, and propose feasible solutions. We believe that this review will advance the application of these technologies in treating waste lye and residue, thereby significantly contributing to the efficient recovery and utilization of seaweed gel extraction waste.

Main text

The technological process of seaweed gum extraction

At present, the extraction methods for seaweed gels, including agar and carrageenan, typically involve an alkaline process. The extraction process, in conjunction with the actual production workflow, is illustrated in Fig. 1. The steps include obtaining raw seaweed materials, alkali treatment, neutral cleaning, acidification, further cleaning, bleaching, additional cleaning, gel cooking, filtration, cooling, pressure filtration dehydration, and drying, resulting in the final products. A high content of sulfate groups in algae can weaken the strength of the extracted seaweed gel. As a traditional method for extracting seaweed gel, alkali treatment facilitates the conversion of

Table 1 Total output of seaweed processing waste in different regions and years in China. (Unit: ten thousand tons)

	Jiangsu	Zhejiang	Fujian	Shandong	Hunan	Guangxi	Total
2019	0.75	247.48	2242.16	766.82	10.05	226.03	3493.28
2020	10.80	251.10	2143.92	766.81	10.05	226.03	3408.71
2021	10.80	241.00	499.33	1052.59	10.30	226.03	2040.05
2022	11.81	14.98	523.56	10.050	10.30	226.63	797.32
2023	1.76	16.13	548.98	10.352	42.66	216.06	835.96

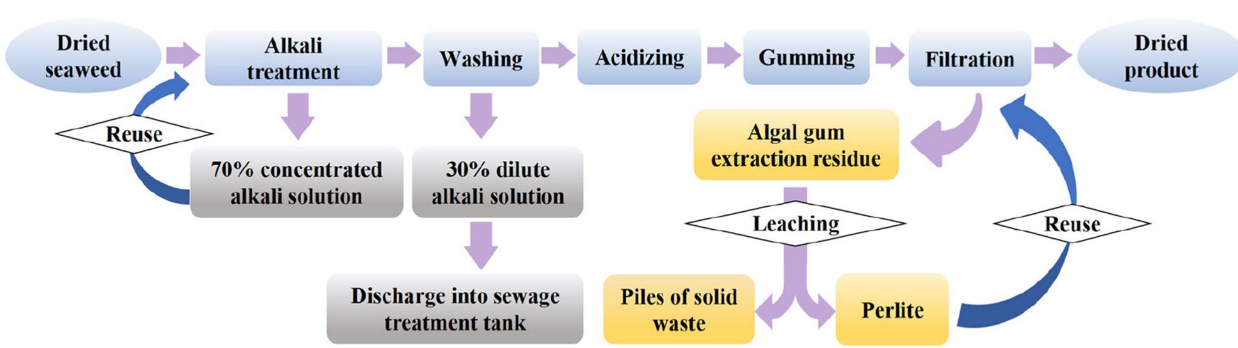


Fig. 1 Flow chart of the seaweed gel extraction process

L-galactose-6-sulfate to 3,6-dehydrated L-galactose, thereby eliminating sulfate groups within the gel [17]. Consequently, appropriate alkaline treatment has become a widely adopted step in the extraction of seaweed gels.

Waste generated during the seaweed gum production process

During the alkali treatment process, alkali interacts with the cell wall of the seaweed, leading to the dissolution of organic matter such as pigments, polysaccharides, and proteins found in the algae. Following this reaction, the lye changes from a transparent state to a black solution, commonly referred to as black lye. Typically, industrially produced lye is reused 2 to 3 times. However, when the organic substance concentration is too high and the solution becomes viscous, it is no longer suitable for further use. After alkali treatment, most of the alkali remains in the solution, while approximately 30% is retained in the seaweed. This residual alkali must be neutralized through repeated washing and acidification, which results in significant resource consumption and the discharge of waste alkali solution. The cost of wastewater treatment has risen [18], posing an environmental burden. Although alternative methods such as microwave-assisted extraction [19], ultrasound-assisted extraction [20], and enzyme-assisted extraction [21, 22] are more environmentally friendly, the large-scale production of seaweed gel remains unfeasible due to production costs and other factors [23].

In the production process, filtration can lead to the formation of a film that hinders colloid filtration due to the gel characteristics. To address this issue, perlite is added as a filter aid, which facilitates the smooth filtration of the glue liquid and enhances the filtration speed. Perlite filter aids possess large specific surface areas and unique pore structures [24]. On one hand, they can prevent the formation of the film; on the other hand, they can absorb certain impurities present in the alkali solution. However, during the extraction of seaweed gel, a significant amount of solid residue (seaweed gel extraction residue) remains. In addition to perlite, this residue contains a substantial quantity of organic substances. Disorderly accumulation of this residue can lead to the production of numerous pollutants, such as corruption, methane greenhouse gases, and sulfides, which can severely impact the environment [25].

Taking carrageenan as an example, the residue produced during its production contains a significant amount of perlite. Li et al. 2024 [26] designed an eco-friendly recovery scheme for perlite by combining hydrochloric acid and hydrogen peroxide. Under this recovery scheme, they observed that the inner ether galactose ring within the carrageenan residue was degraded by hydrogen peroxide and hydrochloric acid, resulting in potassium being repeatedly adsorbed and released as the number of recovery cycles increased. The perlite recovered using this method demonstrated improved performance. Meanwhile, Yu et al. 2023 [27] investigated industrial wastewater at the molecular level using Fourier transform ion cyclotron resonance mass spectrometry. This wastewater primarily consists of humic substances, aromatic compounds, and proteins. After treatment with a membrane bioreactor and nanofiltration, these components are easily biodegraded into high-oxygen, high-unsaturation, and aromatic compounds. This transformation largely depends on the variations in the H/C and O/C ratios of the organic elements. In a study by Wei et al. 2020 [28], cations present in the waste liquid interacted with organic matter, leading to the condensation of the organic matter. Collectively, these studies indicate that the elemental composition and structure of the waste may be altered due to the effects of treatment methods and environmental conditions.

Current treatment status of waste lye from seaweed gel extraction

According to the current alkali treatment process, producing one ton of seaweed gel products consumes between 8.08 and 10.5 tons of alkali and generates approximately 460 to 600 tons of low-concentration alkali washing wastewater. Presently, the primary use of waste lye in factories is to supplement alkali liquid for colloid extraction. However, if alkali is reused more than seven times, the chemical oxygen demand (COD) can exceed 100,000, rendering the process unsustainable. Taking Fujian Province in China as an example, nearly 100,000 tons of high COD waste lye are produced annually. Given the characteristics of high COD, elevated salinity, high alkalinity, and significant water consumption, many researchers have investigated this issue. Currently, the main treatment method employed by factories involves neutralizing the lye and transferring it to sewage treatment plants for activated sludge degradation. However, this approach does not fully utilize the active substances present. Furthermore, the treatment process necessitates a substantial amount of acid, resulting in high treatment costs.

In the waste lye produced during algal gum extraction, there is a high concentration of alkali, along with various organic active ingredients dissolved in the algae, including pigments, polysaccharides, proteins, and other organic matter. These components are typically recycled during the treatment of waste lye. Zong et al. 2016 [29] reported effective adsorption using activated carbon. The activated carbon was added to the filtered lye, and the mixture underwent secondary cleaning to remove impurities. They assessed the impurity content of the lye using the drying-w weighing method and concluded that the alkali could be recycled. However, activated carbon that has reached adsorption saturation cannot be reused, which increases the risk of other pollutants. Wan et al. 2020 [30] employed electrochemical oxidation to treat alkali-treated seaweed via electrolysis, conducting electrochemical reactions with equivalent electrochemical properties at both the anode and cathode of Ru-iridium titanium. The alkali rapidly transferred from the seaweed to the solution, facilitating the swift removal of alkali from the seaweed [31]. This method offered a novel perspective for addressing the issue of excessive water consumption; however, it did not incorporate the recovery of organic substances from the alkali solution. Building on the high nutrient content found in wastewater, Zhao et al. 2020 [32] utilized green algae to treat wastewater generated from agar production. They successfully achieved wastewater treatment by absorbing inorganic nitrogen and phosphorus, yet a suitable scheme for the treatment of waste lye remains elusive. The aforementioned methods focus on the direct treatment of lye extracted from seaweed gel or the wastewater produced during subsequent lye cleaning. These treatment strategies failed to utilize waste lye, thereby contributing to additional environmental pressures.

Current treatment status of solid waste residue from seaweed gel extraction

According to preliminary statistics, the production of one ton of seaweed gel generates approximately 2.5 tons of waste residue (dry basis). The annual production of seaweed gel extraction residue in Fujian Province exceeds 35,000 tons (dry basis). Currently, there is a limited amount of research on the treatment of seaweed gel extraction residue in industrial settings. Aside from minimal recycling efforts at fertilizer plants, researchers have primarily focused on utilizing seaweed gel extraction residue as animal feed. In the study conducted by Li et al. 2016 [33], a 0.10% fermented sediment culture was incorporated into standard piglet feed to enhance the microbial flora in the rectum of the piglets. Additionally, 1% fermented sediment was added to the basic feed of pregnant sows to improve their intestinal flora [34]. In recent years, agar extract residue has been utilized to produce insoluble dietary fiber [35]. Although these studies aim to recycle the algal components found in the residue, the overall utilization rate remains low. Consequently, a significant proportion of seaweed gel extraction residue continues to accumulate as solid waste, treated as industrial landfill. The large volume of waste residue containing perlite poses a threat to the ecological environment and results in resource wastage due to the underutilization of the primary components present in the waste. In summary, it is essential to select an appropriate scheme for the efficient recycling of waste lye and waste residue generated by the algal gel industry. This initiative not only plays a significant role in the seaweed gel sector and its associated food and pharmaceutical industries but also positively contributes to the promotion of seaweed aquaculture and the protection of the marine ecological environment.

The treatment technologies for waste lye from seaweed gel extraction

In addition to its alkaline properties, waste lye contains various active constituents, including polysaccharides, polyphenols, and flavonoids [36]. As illustrated in Fig. 2, the current treatment methods comprise neutralization, electrolysis, concentration, electrodialysis, and diffusion dialysis [37]. Among these, electrodialysis and membrane concentration, along with other membrane-related technologies, are more widely employed.

Application of electrolysis in waste lye treatment

Electrolysis is commonly employed to treat alkaline wastewater that contains high levels of organic matter. An electrooxidation generator is utilized to process the sewage discharged from the secondary sedimentation tank of the park sewage treatment plant [38]. Electrooxidation, noted for its efficiency and environmental friendliness, effectively decomposes pollutants. Park et al. 2013 [39] demonstrated the use of an electrochemical reactor for degrading urban sewage rich in organic matter and colloids. Although the molecular hydrogen generated during electrolytic reactions can degrade organic matter, the concentrations of dissolved organic carbon, carbohydrates, and organic acids remain unchanged. Ntagia 2020 [40] reported that alkali from waste lye produced in chemical manufacturing can be recovered through the electrolytic cell reaction in a bipolar chamber operating continuously for 20 days. The anode reaction in the electrolytic process eliminates active sulfides from the waste lye, while the cathode facilitates alkali recovery, thereby confirming that electrochemical treatment is an economical and viable method for alkali recovery.

Application of electrodialysis in waste lye treatment

Electrodialysis is a separation technology grounded in electrochemical principles. By applying an electric field between two electrodes, it facilitates the selective transmission of charged ions across a membrane, enabling the separation and removal of ions. This technology has found extensive applications in food processing, salt production, and wastewater treatment [41]. Zagorodnyaya et al. 2019 [42] refined coarse ammonium perrhenate salt through recrystallization, adsorption, and membrane

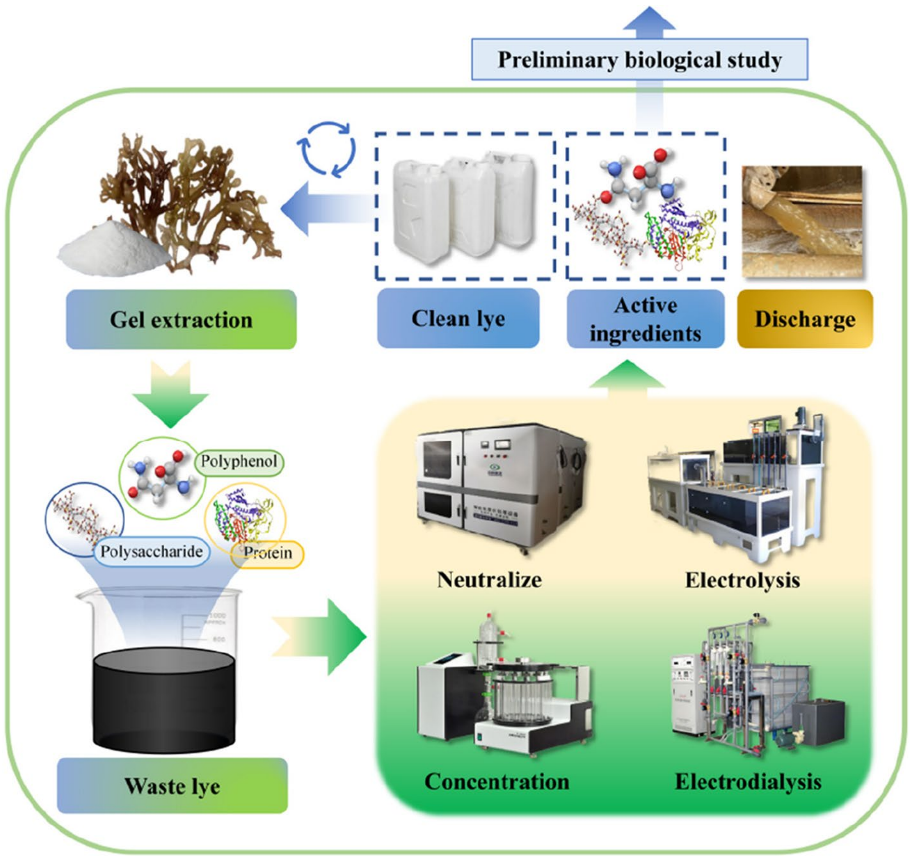


Fig. 2 The treatment technologies for waste lye from seaweed gel extraction

electrodialysis, achieving purification by removing impurities and standardizing rhenium. Their results indicated that electrodialysis purification could yield pure salt with an efficiency of 82.5%, outperforming the purification achieved through recrystallization and adsorption. Chen et al. 2021 [43] reported that electrodialysis effectively removes metal ions from green tea soup, significantly reducing the concentrations of $Ca2^+$, K^+, and $Mg2^+$ ions, thereby decreasing the turbidity of the tea soup. These findings suggest that electrodialysis can enhance the quality of green tea soup.

Application of concentration membrane in waste lye treatment

The concentration membrane is a semipermeable membrane composed of a specific material featuring a microporous structure that enables the selective transport of substances [44]. This process relies on the size, shape, charge, and interaction between the solvent and the membrane, allowing solutes to be transported through the membrane in various ways to achieve separation and purification [45]. In 2015, Hu [46] employed ceramic membrane filtration as a substitute for traditional plate frame filtration to pretreat lincomycin fermentation broth. The feasibility of this approach was assessed by optimizing the filtration conditions of the fermentation broth and measuring the average flux of the ceramic membrane along with the recovery rate of lincomycin. The results indicated that the optimal average flux and recovery rate of the ceramic membrane filtration process surpassed those of the plate frame filtration method.

Li 2011 [47] utilized a nanofiltration membrane to effectively remove most of the organic matter from the black lye of paper. The recovered lye meets reuse standards, and the concentrated liquid can be employed for desulfurization in power plants, thereby saving energy and generating new economic benefits. Yu 2013 [48] employed polymeric coagulants, such as polyacrylamide, to pretreat mercerized lye. The organic matter in the alkali solution was eliminated using an acid–alkali nanofiltration membrane, facilitating alkali recovery in accordance with cleaner production requirements. Li et al. 2020 [49] combined quaternized graphene oxide with quaternized poly(vinyl alcohol) or quaternized ammonium polyethyleneimine. Subsequently, the mixture was cross-linked with formaldehyde to produce a composite anion exchange membrane. The membrane's weight remained largely unchanged even after immersion in a 2 mol/L NaOH solution at 60 °C for 32 days, demonstrating that the composite membrane possesses alkali stability and is suitable for electrodialysis alkali recovery. Liu et al. 2014 [50] prepared a cation exchange membrane using polyvinylidene fluoride and sodium p-styrene sulfonate as raw materials. This membrane exhibits good alkali stability and has been successfully applied to alkali recovery through diffusion dialysis at various temperatures. Li et al. 2019 [51] acidified black lye with sulfuric acid and recovered alkali via electrolysis. After 24 h of electrolysis, the alkali recovery rate reached 50.64%, achieving the recycling of waste lye.

Application of electrochemical techniques combined with membrane in the treatment of waste lye

Membrane-related electrochemical techniques for treating waste liquids generated by modern industry have been increasingly reported, leading to the development of acid/alkali anti-ion exchange membranes. However, these methods of treating waste lye require significant amounts of water and acid, and the organic substances in the waste lye often cannot be effectively recycled. Xie 2021 [52] applied electrodialysis technology to treat waste lye produced from the extraction of seaweed rubber. This technology is characterized by low energy consumption and simple pretreatment processes, allowing for the concentration and desalination of the solution without phase change. It effectively separates the alkali solution from organic matter, yielding a highly alkaline solution with a cumulative recovery rate of 37%. Additionally, waste lye can be treated with low energy consumption while achieving efficient recovery.

Xu et al. 2015 [53] employed multistage membrane concentration technology to recover tea polyphenols and other active substances from tea waste, achieving retention rates of 70%, 79.3%, and 83.8%, respectively. The multistage membrane was cleaned with sodium hydroxide to restore membrane flux, resulting in flux recovery rates of 100%, 95.9%, and 96.1%, respectively. This multistage membrane can be reused while retaining the biological activity of tea polyphenols. In summary, the combination of electrodialysis and membrane concentration for treating waste lye from seaweed gel enables the efficient recovery and utilization of organic active substances, such as polysaccharides and polyphenols.

The treatment technologies for solid waste residue from seaweed gel extraction

In addition to comprising 70% perlite, the solid waste from seaweed gum also contains trehalose (50%), protein, and polyphenols [54]. Furthermore, recycled perlite can be utilized for the extraction of seaweed gel. Lei et al. 2024 [55] successfully developed a functional composite membrane from algal residue by utilizing biomimetic mineralized zirconia nanoparticles (ZrO NPs), which exhibit properties for fluoride removal, uranium extraction, and antibacterial activity. Liu et al. 2010 [56] synthesized carboxymethyl cellulose from the agaric extraction residue of Gracilaria, demonstrating the significant recycling potential of this waste material. As illustrated in Fig. 3, domestic and international technologies for the treatment and recovery of algal gel waste primarily include calcination, chemical degradation [57], and enzyme degradation [58, 59].

Application of calcining technology in solid waste treatment

Rangsriwatananon et al. 2008 [60] proposed utilizing roasting to modify and recover filter aids from waste slag. Tunklová et al. 2022 [61] converted tea waste into soil amendments and potential biofuels through high-temperature roasting. Shih et al. 2021 [62] subjected diatomaceous earth waste to heat treatment at 200 °C to eliminate impurities. However, the heat treatment of waste residues is costly and may contribute to air pollution issues [26].

Application of chemical degradation in solid waste treatment

Chemical degradation encompasses oxidation, acid degradation, and alkali degradation. In alkaline solutions, the glycan chain of polysaccharides may be partially degraded, leading to the detachment of sulfate groups. It is widely accepted that the antioxidant activity of polysaccharides is associated with their sulfate groups [63]. Consequently, alkali degradation is not commonly employed for the degradation of seaweed polysaccharides; rather, acid or enzymatic degradation is preferred. However, the use of acid hydrolysis generates waste acid, which is detrimental to resource conservation and environmental protection.

Application of enzyme degradation technology in solid waste treatment

Enzymatic degradation plays a crucial role in solid waste treatment. This process is gentle and can transform waste residues into organic fertilizers, bioenergy, or other active substances, typically without generating additional waste. Wang et al. 2019 [64] extracted non-reducing polysaccharides characterized by smooth surfaces, minimal folds, good water solubility, and thermal stability through ultrasonic-assisted extraction. Liu et al. 2022 [65] utilized recombinant alginate lyase to degrade alginate, resulting in the preparation of unsaturated alginate oligosaccharides with broad-spectrum antiviral and bactericidal

Fig. 3 The treatment technologies for solid waste residue from seaweed gel extraction

effects. In another study, Wang et al. 2003 [66] employed acid hydrolysis to degrade carrageenan. The agar extraction residue contains approximately 30% Gracilaria residue [67], with the total cellulose and hemicellulose content in Gracilaria residue reaching 65.71% [68]. Additionally, the fibers within the pores of perlite can be effectively degraded with the addition of enzymes.

Application of enzymatic method combined with chemical method in waste residue treatment

Although significant progress has been made by both domestic and international scholars in the research on the resource utilization of seaweed waste residue, the current industrial extraction processes for seaweed gel have not been fully simulated. Additionally, the recovery of perlite filter aids has not been addressed, resulting in inadequate solutions to the waste residue treatment issues within the seaweed gel industry. Calcination, while a possible treatment method, substantially increases production costs for enterprises and introduces new environmental pollution concerns. Although other chemical methods can treat waste residue, they often fail to fully recover the main components.

Li et al. 2022 [69] enzymatically treated nearly 50% of the polysaccharides present, excluding perlite, and successfully obtained specific active oligosaccharides, including neoagarobiose, neoagarotetraose, cellobiose, and cellotriose, which initially cleaned the pores of perlite. Concurrently, hydrochloric acid and hydrogen peroxide were utilized to chemically treat certain components, resulting in the degradation of most polysaccharides within the perlite pores. This further cleaning restored the pore structure of the perlite. Therefore, a combination of enzymatic and chemical methods can effectively recover specific active oligosaccharides and perlite, facilitating the separation and recycling of perlite filter aids and seaweed polysaccharides. It is essential to address the substantial solid waste generated during the production of seaweed gel and to achieve the resource and high-value utilization of seaweed gum extraction waste residue.

The key problems in the recycling of organic active substances in waste from seaweed gel extraction

Compared to neutralization, incineration, and other methods, electrodialysis combined with membrane concentration demonstrates superior effectiveness in treating waste lye. However, the impact of charges generated during electrolysis should not be overlooked. Ilhan et al. 2015 [70] utilized high-intensity ionic pollutants at landfill sites for wastewater treatment, investigating the electrodialysis devices' capacity to treat wastewater and recover ions removed by acid/alkaline solutions. Bipolar membrane electrodialysis achieved higher concentrations of acids and alkalis, but the adsorption of organic substances adversely affected the recovery rates. Xu et al. 2021 [71] employed nanofiltration membrane technology to separate sulfuric acid and salt from the anode liquid in an electrodeposited nickel process, subsequently concentrating and recovering sulfuric acid through electrodialysis. Although these electrodialysis methods can recover waste lye, the recovery rates are influenced by the presence of organic matter and charges in the waste lye.

Xie et al. 2024 [72] reported that during electrodialysis, charges are adsorbed by organic substances and accumulate on the surface of the permeable membrane medium, thereby reducing the lye recovery rate. As illustrated in Fig. 4, the recovery utilization of alkali and the activity of organic polysaccharides are impacted by the release of charge during multimembrane concentration, which has emerged as a critical scientific challenge in the industrial recovery and application of organic active substances from the waste base of seaweed gel.

The treatment of waste residue typically involves the conversion of organic chemical bonds, which is closely linked to the transformation of energy generated by specific enzymes. The cleavage of the glycan backbone occurs when a hydroxyl radical extracts a proton from the carbon in the glycosidic bond [73]. The active group of the oxidant can capture the proton at the 1 or 4 positions of the β-1,4 glycosidic bond in polysaccharides, leading to non-enzymatic oxidative cleavage of the glycosidic bond and resulting in water-soluble polysaccharides [74]. Enzymes are capable of catalyzing the cleavage of glycosidic bonds in polysaccharide macromolecules, producing oligosaccharides with a low degree of polymerization [75]. Shi et al. 2018 [76] employed a combination of pectinase and glucose to degrade enteromorpha polysaccharides. The results indicated that this combination significantly reduced the molecular weight of enteromorpha polysaccharides without altering their structure. Furthermore, the antioxidant activity of the polysaccharides subjected to enzymolysis was notably enhanced. These studies demonstrate that the integration of enzymatic and chemical methods can effectively treat waste residue and recover perlite. However, organic material conversion and energy interactions occur during solid–liquid separation. As illustrated in Fig. 5, the structural activity and recovery of organic polysaccharides are influenced by the specific structure of the enzyme.

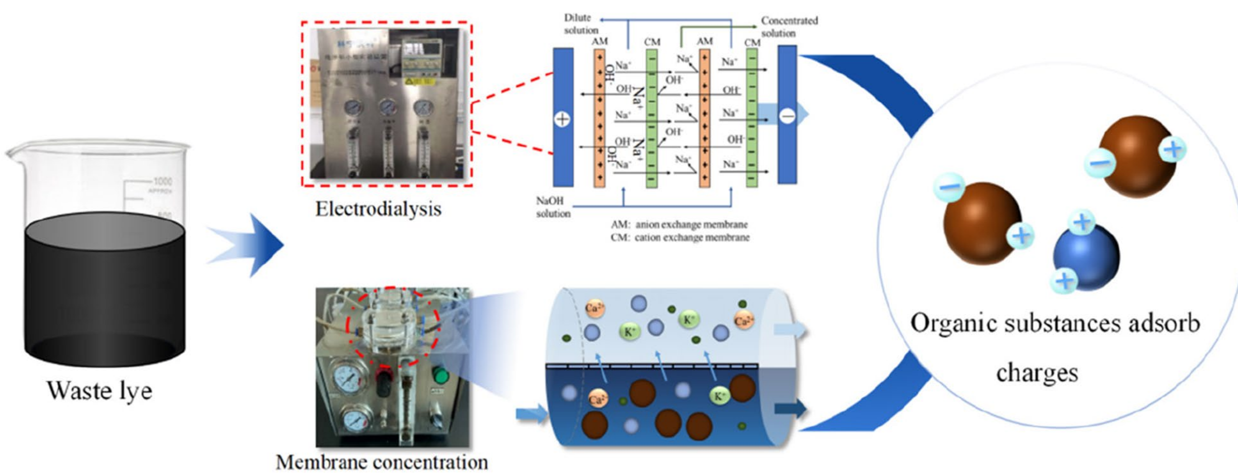


Fig. 4 Speculating the mechanism of charge affecting the electrodialysis membrane and membrane concentration process

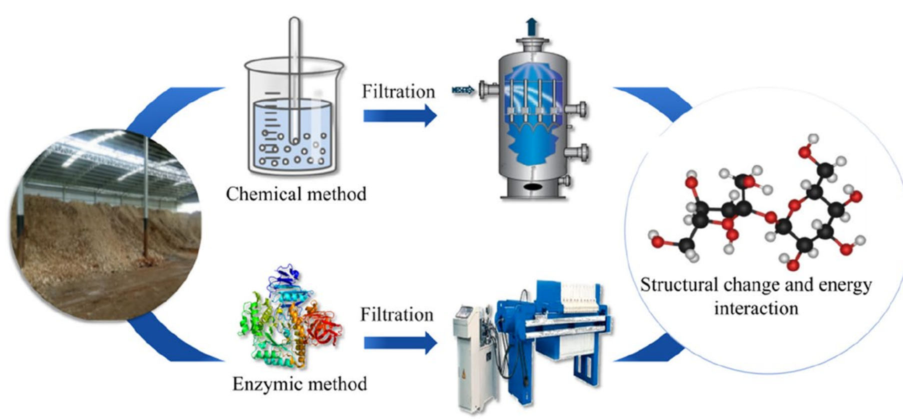


Fig. 5 Speculating the mechanism of the effects of enzymatic and chemical treatments on the structure and activity of organic matter

Study on the adsorption mechanism of organic matter in waste lye

As illustrated in Fig. 6, the treatment of waste lye through electrodialysis combined with membrane concentration facilitates the easy adsorption of charges by organic substances. These organic substances accumulate on the surface of the permeable membrane, thereby reducing the permeability of the interpermeable membrane and negatively impacting the recovery rate of the lye. Trace-charge analysis is commonly employed for detecting and quantifying low concentrations of charged particles or ions within a sample. By integrating Scanning Electron Microscopy (SEM) with trace-charge analysis, one can investigate the degree of aggregation of organic active substances, as well as the adsorption charge and charge release on the membrane surface. A charge diffusion model will be established to study the transport and release of charges during the electrodialysis combined with membrane concentration. These research methodologies were utilized to explore the effects of various factors, including different charge conditions, pressures, flow rates, and membrane pore sizes, on alkali recovery and the activity of organic substances. Ultimately, this study aims to elucidate the mechanism behind the adsorption of organic substances in waste lye.

Zhao et al. 2019 [77] investigated the adsorption behavior of organic substances on anion exchange membranes (AEMs) during electrodialysis. These organic substances, which possess negative charges, exhibit diverse structures. Scanning electron microscopy analysis revealed that organic compounds containing benzene rings demonstrate stronger adsorption on AEMs, significantly restricting the migration of transmembrane ions. Merkel et al. 2024 [78] proposed a comprehensive two-dimensional computational model based on the mass–charge transport conservation equation. This model was employed to examine multi-ion transport and the kinetics of electrode acidification in skim milk using bipolar membrane electrodialysis. Zhai et al. 2022 [79] utilized a quartz crystal microbalance with dissipation monitoring capabilities to conduct a microscopic analysis of the influence of cations (Na^{+}) on membrane fouling. The results indicated that Na^{+} significantly affected the adsorption of organic polysaccharides onto the membrane, likely due to alterations in the internal molecular structure of the organic matter following $Na+$ adsorption. Consequently, the extent of organic matter accumulation on the membrane varies.

Study on the mechanism of activity change and energy interaction of organic matter (polysaccharides) in waste residue

The recovery of perlite and organic materials (specifically polysaccharides) from seaweed gel can be achieved through chemical treatment. In the initial phase, the author's research group successfully isolated bioactive agar oligosaccharides and cellulose oligosaccharides, along with perlite, using enzymatic and acid-assisted methods [69]. The recovered perlite exhibits properties

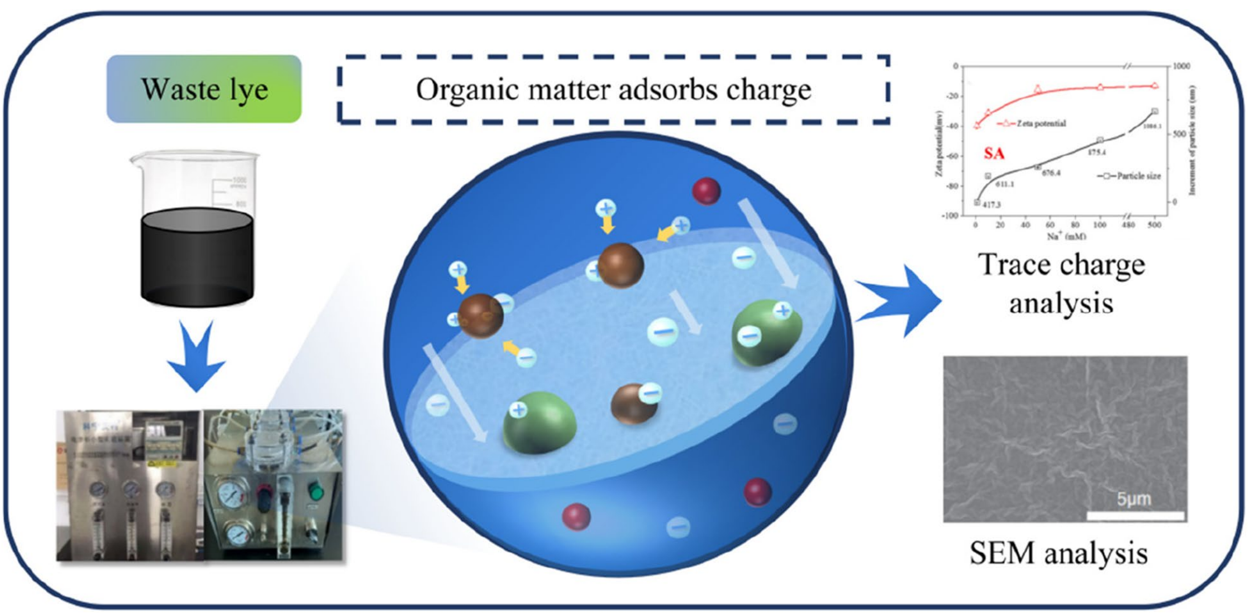


Fig. 6 Study on the mechanism of the adsorption of organic matter from waste lye during seaweed gel extraction

comparable to commercial perlite and can be reused in related industries [80–82]. However, during the solid–liquid separation of the treated waste residue, organic material conversion and energy interactions occur under the influence of specific enzymes, as illustrated in Fig. 7. These factors may affect the structural activity and recovery of organic polysaccharides.

This issue can be investigated through microcalorimetric analysis and structural dynamics simulations of specific enzymes. Furthermore, a thermodynamic model can be developed to examine the energy changes in waste residues during the recovery process. Structural alterations in the organic matter (polysaccharides) can be detected using scanning electron microscopy (SEM). The vibration amplitude and functional groups associated with the characteristic absorption peaks of the recovered organic matter will be analyzed through Fourier transform infrared (FT-IR) spectroscopy. Additionally, the impacts of elemental composition and changes in chemical bonds on the structure of the recovered photoactive polysaccharides can be assessed using X-ray fluorescence spectroscopy and X-ray photoelectron spectroscopy. Ultimately, by integrating these research methodologies, the mechanisms of organic matter activity transformation and energy interactions in the extraction waste residues can be elucidated.

Lu et al., 2022 [83] studied lignin extracted from bioethanol production residue by enzymatic hydrolysis. The pyrolysis behavior and kinetics of the lignin-modified products were investigated by thermogravimetric analysis combined with Fourier transform infrared spectroscopy (TG-FTIR). The above research revealed a correlation between the pyrolysis performance of lignin-modified products and the change in graft functional groups. Morais et al., 2020 [84] studied the change in the potential energy of bagasse after enzymatic hydrolysis. In the enzymatic analysis of laccase and manganese peroxidase (MnP), FT-IR was used to determine the time of lignin degradation due to CH_3 extension. The correlation between the change in potential energy and the change in substance structure during the enzymatic hydrolysis of bagasse was analyzed by scanning electron microscopy. The above discussion provides a feasible scheme for studying the charge adsorption mechanism, organic material activity transformation, and mechanism of energy interaction in seaweed extract waste residue.

Outlook and future study direction

Based on the preliminary research conducted by the authors'research group, we propose an effective method for recycling waste generated from seaweed gum production. Electrodialysis combined with membrane concentration technology is employed to treat the waste lye. The chemical oxygen demand (COD) removal rate and alkali recovery rate of the waste lye processed by electrodialysis reached 69.97% and 45.31%, respectively. Following the optimization of process conditions, the optimal parameters for membrane concentration were identified as a pressure of 0.50 MPa, a flow rate of 40 L/h, and a pore diameter of 1000 Da. Under these conditions, the maximum COD removal rate and alkali recovery rate achieved were 68.46% and 11.20%, respectively [72]. For the recovery of waste residue, we propose a green recovery scheme utilizing perlite combined with food-grade hydrochloric acid and hydrogen peroxide, resulting in a perlite permeability of 2.61 Darcy, which meets the reuse standard and demonstrates significant economic value [26].

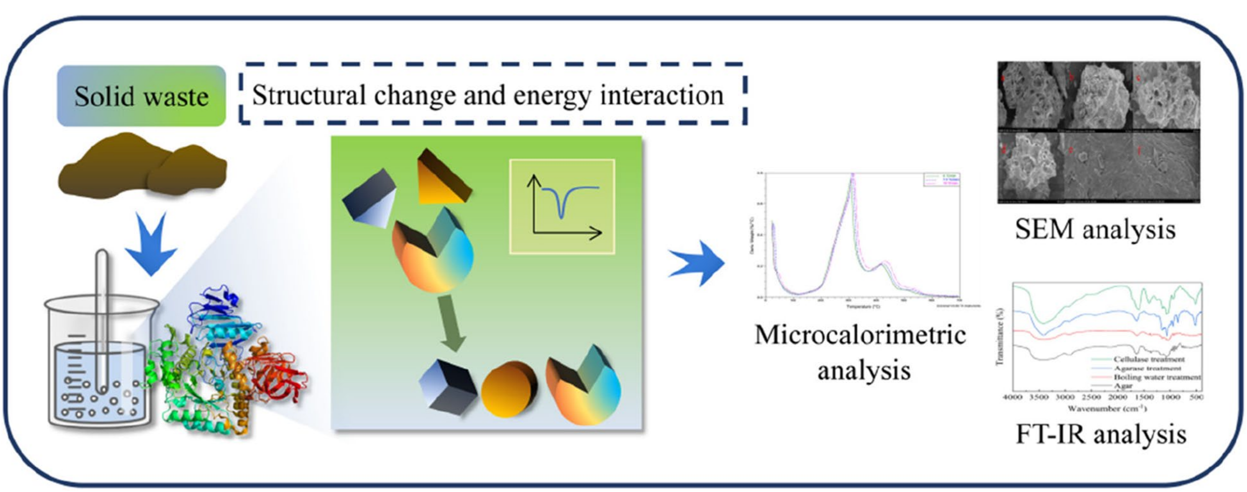


Fig. 7 Study on the mechanism of activity change and energy interaction of organic matter (polysaccharides) in waste residue

The study of recycling waste generated from seaweed gum production is highly valuable. Firstly, it can minimize waste generation and environmental pollution during the production process, while also enhancing the recovery efficiency of lye and perlite. Secondly, many active substances present in the waste lye and residue can be re-extracted and utilized in various fields, thereby maximizing the utilization of seaweed resources.

The study of recycling waste generated from seaweed gum production is highly valuable. Firstly, it can minimize waste generation and environmental pollution during the production process, while also enhancing the recovery efficiency of lye and perlite. Secondly, many active substances present in the waste lye and residue can be re-extracted and utilized in various fields, thereby maximizing the utilization of seaweed resources.

Conclusions

The substantial amounts of waste lye and residue generated during the production of seaweed gel pose significant challenges for efficient recycling. The high organic matter content in these wastes severely impacts the environment following discharge. Electrodialysis, combined with membrane concentration, as well as the integration of enzymatic and chemical methods, are effective strategies for treating waste lye and residue while recovering organic substances. However, organic substances in the waste lye tend to adsorb charges and block the permeable membrane, leading to a reduced recovery rate of the lye. In solid waste residue, the structure and activity of organic substances are altered by specific enzymes. Practical approaches for examining these issues include trace-charge analysis, charge diffusion modeling, microcalorimetric analysis, thermodynamic modeling, and scanning electron microscopy. These techniques can elucidate changes in the organic structure and membrane aggregation during electrodialysis, as well as the structural and energy transformations of polysaccharide degradation induced by specialized enzymes. By employing these methods, key challenges in waste recovery can be addressed, facilitating the efficient resource utilization of waste lye and solid waste residue.

Abbreviations

ZrO NPs	Biomimetics mineralized zirconia nanoparticles
AEM	Anion exchange membrane
QCM-D	Quartz crystal microbalance with dissipation monitoring
FT-IR	Fourier transform infrared spectroscopy
TG-FTIR	Fourier transform infrared spectroscopy combined with thermogravimetric analysis
MnP	Manganese peroxidase
SEM	Scanning electron microscopy

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Authors' contributions
XZL: Conceptualization, formal analysis, writing-original draft. YYW:Collecting data. SHW and ZX: Market research. XPD, MJZ and YBZ: investigation. ZDJ, QBL and HN: funding acquisition. ZPL and ZHC: funding acquisition, writing-review and editing, supervision. All authors read and approved the manuscript.

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Data availability
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Declarations

Ethics approval and consent to participate
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Competing interests
The authors declare no competing interests.

Author details
[1]College of Ocean Food and Biological Engineering, Jimei University, Xiamen, Fujian 361021, China. [2]Fujian Provincial Key Laboratory of Food Microbiology and Enzyme Engineering, Xiamen, Fujian 361021, China. [3]Research Center of Food Biotechnology of Xiamen City, Xiamen, Fujian 361021, China. [4]Xiamen Ocean Vocational College, Xiamen, Fujian 361021, China.

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