

Marine microalgae-mediated quorum quenching: potential strategies for the sustainable biological control of mangrove ecosystems

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Abstract

The mangrove ecosystem, particularly in Southeast Asia, holds a vital ecological role in the preservation of world biodiversity, coastal protection, and carbon sequestration. Nonetheless, it is confronted with the peril of root infection induced by various pathogenic bacteria. These pathogenic bacteria control biofilm formation and the production of virulence factors via a quorum sensing (QS) mechanism, leading to persistent and challenging illnesses that inflict significant economic losses on the mangrove-associated aquaculture industry. Conventional chemical management approaches not only readily produce drug resistance in pathogenic bacteria but also provide a possible risk to the delicate mangrove ecosystem. This review thoroughly examines a novel green and sustainable biological control strategy—quorum quenching (QQ) facilitated by marine microalgae. We initially detailed the fundamental function of QS in the pathogenicity of pathogenic bacteria, particularly its regulatory mechanisms concerning biofilm formation and virulence expression. The species of marine microalgae exhibiting QQ activity and their mechanisms of action were thoroughly studied, encompassing enzymolysis signal molecules, competitive receptor simulation, and the suppression of signal molecule synthesis. This paper examines the potential applications of marine microalgae-mediated QQ in mangrove ecosystems, addressing various strategies, including the direct colonization of microalgae to safeguard plant roots, the inhibition of *Vibrio* infections in the mangrove aquaculture coupling system, and the enhancement of the anaerobic sediment environment through photosynthesis. This review addresses the obstacles encountered in transitioning microalgae QQ technology from laboratory settings to field applications, including tidal and salinity adaptation, and underscores the necessity of utilizing indigenous microalgae to guarantee ecological security. We contend that QQ in marine microalgae constitutes a promising Nature-Based Solution (NBS), offering an innovative biological control strategy for the health maintenance and sustainable development of mangrove ecosystems.

Full Text

Preamble

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Abstract

mangrove ecosystem, particularly Southeast Asia, holds vital ecological preservation world biodiversity, coastal protection, carbon sequestration.

Nonetheless, confronted peril infection induced various pathogenic bacteria.

These pathogenic bacteria control biofilm formation production virulence factors quorum sensing mechanism, leading persistent challenging illnesses inflict significant economic losses mangrove-associated aquaculture industry.

Conventional chemical management approaches readily produce resistance pathogenic bacteria provide possible delicate mangrove ecosystem. review thoroughly examines novel green sustainable biological control strategy quorum quenching facilitated marine microalgae. initially detailed fundamental function pathogenicity pathogenic bacteria, particularly regulatory mechanisms concerning biofilm formation virulence expression. species marine microalgae exhibiting activity their mechanisms action thoroughly studied, encompassing enzymolysis signal molecules, competitive receptor simulation, suppression signal molecule synthesis. paper examines potential applications marine microalgae-mediated mangrove ecosystems, addressing various strategies, including direct colonization microalgae safeguard plant roots, inhibition Vibrio infections mangrove aquaculture coupling system,and enhancement anaerobic sediment environment through photosynthesis. review addresses obstacles encountered transitioning microalgae technology laboratory settings field applications, including tidal salinity adaptation, underscores necessity utilizing indigenous microalgae guarantee ecological security. contend marine microalgae constitutes promising ature- olution (NBS), offering innovative biological control strategy health maintenance sustainable development mangrove ecosystems.

Keywords

uorum quenching, marine microalgae, mangrove ecosystem, biological control, biofilm inhibition E-mail:

Southeast around one-third global mangrove area. These distinctive coastal wetland habitats serve breeding grounds numerous marine creatures natural

barriers against disasters tsunamis storm surges. crucial effectively sustaining regional ecological equilibrium, supporting livelihoods coastal communities, contributing global carbon cycle Mangroves retain their intricate systems efficiently mitigate coastal erosion, their productivity offers abundant sources habitats fisheries aquaculture. recent years, escalation human activities compounded effects climate change subjected mangrove ecosystems unprecedented disease threats, particularly bacterial pathogens, which often significantly impair growth development mangroves their ecological services.

Conventional disease management methods, including extensive application chemical germicides, exert temporary inhibitory impact harmful microorganisms; nevertheless, their prolonged usage shown numerous disadvantages.

Pathogenic bacteria susceptible developing resistance chemical pressure, leading progressive decline efficacy complete failure treatment Moreover, remnants chemical germicides contaminate delicate biological habitat mangroves, induce toxicity non-target animals, disrupt biodiversity ecosystem stability, potentially bioaccumulate chain, hence posing threats human health. aquaculture systems linked mangroves, application chemical products adversely impact health aquaculture species diminish quality aquatic products.

Consequently, formulation eco-friendly, efficient, sustainable biological management approach replace augment conventional chemical procedures become imperative necessity domain mangrove ecosystem conservation. context, quorum quenching technology increasingly garnering significant attention academic circles innovative biological control

method

Quorum sensing bacterial communication

method

involving secretion detection certain signaling molecules. enables bacteria simultaneously modulate expression attaining sufficient population density, thereby orchestrating collective behaviors biofilm formation, virulence factor secretion, antibiotic resistance essence obstructing pathogenic bacteria manifesting their pathogenic characteristics disrupting dismantling system, rather directly eliminating bacteria, which significantly mitigates resistance pathogenic strains Marine microalgae, significant primary producers mangrove ecosystems, possess diverse array metabolites, including chemicals exhibiting action These microalgae generate oxygen organic matter ecosystem photosynthesis secrete substances effectively inhibit pathogenicity pathogenic bacteria without exerting lethal pressure, thereby offering

green sustainable biological control solution health mangrove ecosystem. review seeks thoroughly evaluate potential marine microalgae safeguarding mangrove

ecosystem health, while examining prospective applications challenges sustainable biological control tool.

2. P

athophysiological mechanism distinctive intertidal habitat mangrove ecosystem offers diverse niche numerous microorganisms while creating optimal conditions survival development certain pathogenic bacteria.

Gram-negative bacteria pathogens causing diseases mangrove ecosystems their associated aquatic products. example, *Vibrio* class gram-negative bacteria prevalent marine environments, which significant marine pathogens threaten human health serve primary pathogenic bacteria aquaculture, including mangrove-associated aquaculture shrimp farming Pathogenic bacteria ocean attack roots mangrove trees aquaculture species, frequently resulting serious diseases, their advanced quorum-sensing regulation system playing crucial their pathogenicity.

2.1 The

significance pathogenicity pathogenic bacteria Quorum sensing intercellular communication mechanism which bacteria synchronize collective action secreting detecting molecular signaling compounds bacterial population density concentration signaling molecules insufficient activate system; nevertheless, bacterial numbers increase, signaling molecules accumulate environment. reaching specific concentration threshold, attach receptors bacterial cells, initiate cascade expression, affect collective behavior bacteria N-acyl homoserine lactones (AHLs) primary signaling molecules gram-negative bacteria signal molecule family comprises various members, such C6-HSL C8-HSL, which roles specific gram-negative bacteria. contrast, quorum sensing signal molecules gram-positive bacteria primarily composed oligopeptides. signal molecules exhibit greater diversity across different bacterial species, mainly including quinolones.

Pathogenic bacteria mangrove illnesses employ system modulate their pathogenic characteristics, including biofilm formation, release virulence factors, tolerance stress Biofilms microbial communities consisting bacteria adhered surfaces encased extracellular polymeric substances (EPS) release mangrove ecosystems, pathogenic bacteria develop biofilms surfaces plant roots aquaculture organisms regulation. development biofilms provides bacteria significant protective capabilities, allowing withstand human immunological responses, antibiotic interventions, environmental stresses, including tidal erosion variations salinity After biofilm formation, bacteria

persistently proliferate secrete virulence factors within leading persistence disease challenges eradication. example, biofilm *Vibrio cholerae* augments environmental viability facilitates cholera transmission biofilm formation *Vibrio* bacteria influenced various mechanisms, including cyclic di-GMP signaling, host-

specific adaptability.

Investigations biofilm control omics technology advanced, demonstrating mechanisms horizontal transfer phase transition augment adaptability biofilms Schematic representation AHL-mediated biofilm-related pathogenicity. bacterial density, Gram-negative pathogens secrete basal levels reach activation threshold. sufficient bacterial density achieved, localized accumulation leads receptor binding, which triggers cascade target transcription.

Consequently, secretion extracellular polymeric substance (EPS) matrix virulence factors induced, driving biofilm formation. resulting mature biofilm provides bacterial community robust resistance against immunity, antibiotics, environmental stresses, thereby ensuring bacterial survival persistent infection.

2.2 QS

control biofilms promotes disease persistence system pivotal development pathogen biofilm. population density pathogenic bacteria attains specific threshold, signaling molecules activate pertinent genes facilitate manufacture release extracellular polymeric substances. predominantly consists polysaccharides, proteins, nucleic acids, which provide framework biofilms, firmly binding bacterial cells creating physical barrier structure safeguards bacteria within biofilm against effects external detrimental influences. adsorb antibiotics impede their infiltration biofilm, resulting increased antibiotic resistance among bacteria inside biofilm

Furthermore, modulates secretion virulence factors pathogenic bacteria.

These virulence factors encompass, restricted hemolysin, protease, cytotoxin, which directly inflict cells, obliterate tissues, consequently induce illness symptoms *Vibrio alginolyticus* significant pathogen responsible vibriosis mangrove-associated aquaculture species shrimp, expression virulence factors regulated pathogenic bacteria establish biofilms mangrove roots surface shrimp, interior milieu promotes prolonged high-level production virulence factors, exacerbating severity duration disease.

Mangrove roots submerged tidal environments, where sediment frequently exists anaerobic microaerobic conditions, hence creating conducive habitats anaerobic facultative anaerobic pathogenic bacteria, *Erwinia* pathogenic bacteria establish biofilms surface, exploit microenvironment within biofilm sustain their physiological activity pathogenicity, unfavorable macro settings. persistence infections mediated biofilms renders conventional physical removal chemical therapies ineffectual.

Chemical germicide eliminate surface bacteria within biofilms, while interior bacteria remain shielded. alleviation chemical pressure, reproduction ensue, resulting illness recurrence.

Consequently, comprehending pivotal function pathogenicity bacteria, particu-

larly biofilm formation, crucial devising innovative effective biological control techniques. targeting critical mechanism, undermines pathogenic capabilities pathogenic bacteria their origin, offering novel perspective remedy health mangrove environment.

3. Microalgal

resources mechanism Marine microalgae, among oldest prevalent organisms Earth, extensively found several aquatic habitats, including mangrove intertidal zone. primary producers marine ecosystem possess highly diversified array metabolites, including polyunsaturated fatty acids, carotenoids, polysaccharides, proteins, numerous secondary metabolites Recent studies increasingly demonstrated numerous marine microalgae their derivatives possess activity, which effectively disrupts system bacteria, thereby inhibiting biofilm formation secretion virulence factors pathogenic bacteria(These findings offer novel concepts formulating eco-friendly biological management strategies utilizing microalgae safeguard integrity mangrove ecosystems.

3.1 Catalog

icroalgae pecies xhibiting otential ctivity Despite limited number studies microalgae specifically aimed mangrove pathogens, several microalgae species exhibiting capability identified extensive marine environments aquaculture disease management research

shown Table activity anti-biofilm impact these microalgae typically accomplished their metabolites interactions commensal bacteria.

Microalgae Observed Activity Effect Species *Phaeodactylum tricornerutum*

Promotion of extracellular products from *B. pumilus* inhibiting biofilm formation by *Aeromonas hydrophila* and *Vibrio anguillarum*

Cyanobacteria antibacterial activity against *Schizochytrium*

Co-culture with microorganisms

Nannochloropsis Nannochloropsis Enhanced biomass antibacterial activity under mixotrophic cultivation *granulata* *Chlorella*

Underlying Mechanism

Representative Literature Production secondary metabolites, possibly indirectly involving interference Cyanobacterial biomass contain components promote production substances symbiotic bacteria, possess activity itself

Production of antibacterial and anti-biofilm compounds, potentially through QQ mechanisms

Complex microbial interactions involve regulation bacterial Production antibacterial compounds, potentially indirectly affecting Antibacterial activity against

Staphylococcus aureus enhanced biomass antibacterial effect under mixotrophic cultivation various bacteria including Pseudomonas aeruginosa effective inhibition biofilm formation enhances biomass lipid accumulation, promotes nutrient cycling

Continued Table Anti-biofilm Potential Related Research Microalgae Observed Activity Effect

Underlying Mechanism

Representative Species Literature Experiments proven substances secretes inactivate molecules competitively bacterial signal receptors. xerts effect inactivating molecules competitively inhibiting receptors.

Chlamydomonas reinhardtii isrupts structure molecules, rendering incapable functioning signaling molecules. secreted substances react -keto-AHLs, thereby inactivating their Nitzschia pellucida activity. aforementioned studies indicate diatoms cyanobacteria, significant primary producers ocean, enhance antibiofilm capabilities other microorganisms mixed culture conditions through their metabolites biomass, directly demonstrate antibacterial activity, implying their potential involvement mechanisms instance, extract Schizochytrium demonstrated direct anti-biofilm action against several bacteria, often associated mechanism These

results

offer comprehensive perspective exploration microalgae exhibiting activity; particularly under optimum cultivation circumstances, microalgae generate increased levels oxylipins hence augmenting their potential.

3.2 Core

m echanism of m icroalgae -m ediated QQ

Recent research revealed marine microalgae mediate through multiple mechanisms, which relatively well-understood mainly summarized following three categories shown Table These diverse interference strategies represent profound evolutionary adaptation forged within highly competitive marine phycosphere, where microalgae bacteria engage continuous chemical secure their ecological niche defend against opportunistic bacterial colonization detrimental biofilm formation their surfaces, marine microalgae evolved biosynthesize array unique secondary metabolites These structurally diverse bioactive compounds serve biochemical foundation activities observed Therefore, exploiting these biochemical foundations holds immense potential sustainable disease mitigation, fundamentally disarming pathogens rather killing them, thereby circumventing escalating global crisis antimicrobial resistance.

Mechanism Action Related Studies Advantages Microalgae either produce enzymes themselves mediate their production associated bacteria, Directly Enzy-

matic Degradation Signals degrades signal molecules, rendering inactive.

Microalgae Produces compounds mimic signal molecules, competitively Signal Mimicry binding receptors blocking authentic signals.

Bioactive compounds microalgae interferes biosynthetic pathways signal molecules within bacteria.

Inhibition Signal Synthesis Bacillus cereus lactonase degrades Stenotrophomona maltophilia Smlt1522 acylase degrades YtnPDH82 enzyme deep-sea Bacillus velezensis efficiently degrades Nitzschia pellucida secretes enzymes directly degrade signaling molecules efficiency specificity; likelihood resistance development.

Strong targeting; Phaeodactylum tricornutum secretes mimic lumichrome, which competitively interferes bacterial directly bacteria, reducing resistance risk.

Fatty acid-derived metabolites marine microalgae interfere pathway, thereby inhibiting bacterial biofilm formation(natural products generally possess potential Reduces signals source; provides sustained effect. lactonases hydrolyze lactone ring; acylases hydrolyze amide bond.

Structurally analogous signal molecules; binds receptors without activating downstream genes.

Inhibits LuxI-type synthase activity, reducing signal molecule production.

3.2.1 Enzymolysis

ignaling olecule represents straightforward comprehensive microalgae mechanisms.

Microalgae mediate effect ways: first, serving carrier recruit enrich bacteria rhizosphere aquatic environments, allowing bacteria become epiphytic, thereby subsequently regulating capability bacteria establish phycosphere microbiome quenching activity.

Secondly, enzymes derived microalgae directly hydrolyze signaling molecules.

Currently, enzymes predominantly originate bacteria.

Numerous bacteria, including those coexist microalgae, possess capability release enzymes degrade alter signal molecules, thereby inactivating them.

N-acyl homoserine lactones (AHLs) represent predominant signaling molecules gram-negative bacteria primary categories enzymes target lactonases amidases. lactonase hydrolyzes lactone AHLs, converting N-acyl homoserine abolishing their signaling action lactonase extracted Bacillus cereus completely digest C6-HSL markedly diminish biofilm formation virulence factor production aeruginosa YtnPDH82 enzyme deep-sea Bacillus velezensis demonstrated remarkable structural stability enhanced breakdown efficiency amidases hydrolyze amide

bonds AHLs, resulting release homoserine lactones related fatty acids, hence diminishing their signaling function smlt1522 protein *Stenotrophomonas maltophilia* functions amidase penicillin amidase, proficient digesting various While these enzymes predominantly synthesized bacteria, microalgae indirectly elicit impact through symbiosis QQ-active bacteria, their metabolites induce augment enzyme activity these bacteria. instance, pumilus cultured medium enriched microalgae cyanobacteria biomass, extracellular products effectively inhibit *Vibrio* biofilms.

However, capacity inhibit biofilm formation diminishes considerably absence microalgae indicating microalgae enhance production enzymes symbiotic bacteria through provision carbon sources other signaling molecules. symbiotic system comprising marine microalgae bacteria, QQ-active bacteria selectively retained enriched, acquire ability produce signals, C6-HSL, during adaptation phycosphere environment Research enzymes derived microalgae revealed certain lactonases *Chlamydomonas reinhardtii* acylases *Anabaena* exist.

Inhibited pathogenic bacteria catalyzing hydrolysis opening homoserine lactone AHLs, irreversibly cleaving amide signal molecules, fundamentally altering molecular structure AHLs; *Nitzschia pellucida* facilitate mechanism natural haloperoxidase system. enzymatic system utilizes hydrogen peroxide facilitate halogenation reaction, specifically targeting -keto AHLs.

HPLC-MS

analysis

verified process

results

ultimate cleavage halogenated N-acyl chain signal molecules, hence entirely abolishing activation activity suggests microalgae possess capability directly implement their intrinsic enzymes.

3.2.1 Signal

imulation ompeting eceptors mechanism entails compounds released microalgae imitate signal molecules bacteria; however, activate receptor.

Instead, competitively receptor, obstructing binding authentic signal molecules, thereby accomplishing objective quenching Halogenated furanones exemplify process.

Originally extracted marine algae, these compounds discovered effectively inhibit system gram-negative bacteria.

Their structures resemble signaling molecules interact receptor proteins bacterial cells; however, structural variations, cannot trigger expression downstream

genes.

Chlamydomonas reinhardtii demonstrated release compounds mimic disrupt bacterial compound lumichrome, riboflavin derivative, synthesized numerous marine primary producers, including *Phaeodactylum tricornutum* *Emiliana huxleyi* which competitively activate receptor, resulting effects certain diatoms dinoflagellates generate halogenated compounds impede biofilm formation which mimicking effects exerted suggests secondary metabolites generated microalgae influence activity simulating disrupting signaling pathways

3.2.2 Inhibition

signal molecule synthesis Another potential microalgae mechanism involves inhibiting synthesis signaling molecules bacteria.

Microalgae disrupt biosynthetic pathways other signaling molecules secreting specific compounds, inhibiting activity LuxI-type LuxS-type synthases. diminishing production signaling molecules, presence bacterial population density, concentration these molecules remain insufficient activate system.

Despite little direct evidence, numerous natural compounds, plant extracts, demonstrated capacity suppress manufacture signaling molecules methanol extract *Portulaca oleracea* inhibit *aeruginosa* phytochemical research revealed phenolic, alkaloid, ester, other substances possess antibacterial antioxidant properties.

Polyphenolic antioxidants their analogous compounds (such curcumin resveratrol) remarkable anti-virulence capabilities. inhibited expression virulence factor genes pathogenic bacteria, guided without directly eliminating bacteria, increased their sensitivity antibiotics. these active substances components secreted metabolites found marine microalgae correspondingly, fatty metabolites -linolenic acid, linoleic acid, secreted microalgae demonstrated highly effective inhibitors pathway.

Interfering system, crucial component biofilm development, diminishes adhesion capacity bacteria surfaces, disrupts structure, inhibits maturation pathogenic bacteria biofilms specific mechanism these metabolites inhibit synthesis

4,5-dihydroxy-2,3-pentanedione (DPD), precursor signaling molecule system, targeting bacterial LuxS-type synthases, thereby preventing different pathogenic bacterial species complex microbial communities synergistically enhancing their pathogenicity through system findings indicate microalgae, repository natural products, include active compounds capable disrupting synthesis bacterial signaling molecules, hence potentially eliciting effects reducing their production bacteria.

Moreover, mixotrophic growing microalgae substantially augment biomass improve their bioactivities, including anti-proliferative antimicrobial actions hence

facilitating large-scale production microalgae activity their extracts. illustration microalgae-mediated mechanisms against bacterial figure illustrates three primary strategies employed microalgae disrupt bacterial communication processes.(A) Enzymolysis signaling molecules.

Microalgae recruit enrich bacteria providing carbon sources secreting signaling molecules, thereby establishing symbiotic phycosphere microbiome (Pathway regulating these symbiotic bacteria produce enzymes, including lactonases amidases).

Alternatively, microalgae directly secrete enzymes themselves (Pathway lactonases, acylases, haloperoxidases).

These enzymes catalyze degradation inactive structural byproducts (e.g., ring-opened N-acyl homoserine, cleaved homoserine lactones fatty acids), thereby inactivating signals consequently mitigating biofilm formation virulence factor expression.(B) Signal simulation competing receptors.

Microalgae synthesize exude signal-mimic compounds (e.g., lumichrome) structurally analogous authentic AHLs.

These mimics competitively bacterial receptors (e.g., LasR) induce functional conformational changes required receptor activation, thereby blocking downstream QS-regulated expression biofilm formation.(C) Inhibition signal molecule synthesis.

Microalgae secrete inhibitory compounds specific fatty acids (e.g., -linolenic acid, linoleic penetrate bacterial cells directly inhibit activity signal synthases (e.g.,LuxS-type synthases). enzymatic inhibition prevents synthesis crucial compound 4,5-Dihydroxy-2,3-pentanedione (DPD), precursor signaling molecule system, leading suppressed activation hindered biofilm development.

4. Potential

application strategies current study extensive marine environment fundamentally indeed offers significant evidence concept biological management mangrove diseases.

Marine pathogenic bacteria utilize quorum-sensing

method

involving other signaling molecules modulate biofilm formation virulence expression, process evolutionarily conserved indicates regardless alterations macroenvironment, bioactive compounds released microalgae either facilitate degradation competitively these highly conserved signaling molecules, fundamental molecular logic remains consistent Therefore, application marine microalgae strategy mangrove ecosystems possesses solid biochemical mechanistic justification.

Bacterial infections mangrove ecosystems primarily attributed *Pseudomonas* *Xanthomonas* *Erwinia* leading disease, black systemic wilt.

These ram-negative bacteria infiltrate plant tissue natural openings, hydathode leaf's margin stomata surface.

Xanthomonas campestris exemplified black infiltrates host's water pore, utilizing low-resistance pathway access vascular system while synchronizing secretion virulence agents mechanism Various Fungal diseases health challenge mangrove ecosystems, pathogenic bacteria *Cytospora* *Pestalotiopsis* *Fusarium* *Colletotrichum* responsible spot, anthracnose, other ailments. mechanism these pathogenic fungi inside mangrove ecosystem requires additional investigation.

Currently, research conservation mangrove ecosystems through symbiotic between marine microalgae mangroves progressed phase rapid advancement majority these studies examine antimicrobial properties symbiotic microalgae mangrove habitats, ecological restoration degraded mangrove wetland ecosystems enhancement mangrove seedling growth demonstrates employing microalgae conservation mangrove ecosystems viable strategy. innovative variant method, application marine microalgae-mediated offers potential multifaceted sustainable biocontrol approach preserving integrity mangrove ecosystems Based this, section proposes three potential application strategies marine microalgae-mediated preserve integrity mangrove ecosystems.

These prospective strategies directly address pathogenic mechanisms pathogenic bacteria while simultaneously enhancing mangrove habitat, ultimately providing comprehensive framework ecosystem preservation.

diagram illustrating multifaceted strategies mediated microalgae mangrove ecosystems. illustration highlights three primary ecological mechanisms:

Protection: Microalgae colonize mangrove roots secrete compounds; concurrently, carriers enrich induce beneficial bacteria, synergistically inhibiting formation pathogenic biofilms surface.

Aquaculture Application: Microalgae release extracellular substances serve functional additives, effectively disrupting systems pathogens (e.g., *Vibrio* safeguard aquatic animals shrimp.

Sediment Oxygenation: photosynthetic activity benthic microalgae releases oxygen, ameliorating anaerobic conditions inhibit proliferation sediment-borne pathogens through indirect effects.

4.1 Microalgae

colonization directly safeguards mangrove roots

system mangrove plants essential material exchange environment serves primary entry point pathogen infection.

Pseudomonas aeruginosa other pathogenic bacteria detrimental mangrove ecosystem attach tenaciously surfaces creating biofilms withstand environmental stressors defenses while persistently releasing virulence factors inflict significant damage roots Colonizing microalgae exhibiting activity mangrove plant roots establish biological barrier, providing immediate protection against pathogen invasion. proposed strategy fundamentally relies interaction between microalgae microbial population present surface.

Microalgae serve carriers probiotics prebiotics disrupt system pathogenic bacteria rhizosphere probiotics produced chemicals, consequently reducing biofilm formation expression virulence factors directly synthesize compounds inhibit pathogenic bacteria. example, Quercetin, secondary metabolite derived marine microalgae, which actively released water microalgae under stress competing pathogenic bacteria,

flavonoid having antibacterial effects effectively suppress biofilm development *Staphylococcus Aureus* validated using

analysis

disrupt diminish expression biofilm-related genes demonstrated capacity natural products impede biofilm formation mechanisms, indicating microalgae generate analogous chemicals stimulate rhizosphere bacteria synthesize enzymes.

Several studies validated efficacy bacteria managing plant diseases, exemplified salt-tolerant *Bacillus toyonensis* AA1EC1 strain derived *Arthrocaulon* which exhibits plant growth-promoting (PGP) properties ability degrade AHLs, thereby markedly diminishing virulence plant pathogens Lactic bacteria, including *Lactiplantibacillus plantarum* WPL10, demonstrate inhibitory activity, positioning prospective biocontrol agents mitigate bacterial pathogenicity biofilm formation selection exogenous application bacteria enable establish symbiosis marine microalgae within mangrove ecosystems, where their capacity modulated enhanced microalgae These works establish theoretical practical foundation application microalgae mediated mechanism safeguarding plant roots.

Microalgae inhabit surfaces mangrove roots. Besides direct effect, augment protective effect through competitive exclusion, competing pathogenic bacteria nutrients attachment sites; secreting antibacterial substances directly eliminate inhibit growth pathogenic bacteria inducing plant resistance, thereby enhancing plant's defense against pathogenic bacteria. facilitate successful colonization microalgae mangrove roots, essential identify local indigenous microalgae species exhibit strong adaptability mangrove ecosystem conduct thorough investigation intricate interactions among microalgae, mangrove flora, rhizosphere microbial communities Furthermore, refining particular colonization approach enhance protective efficacy colonizing microalgae.

Benthic microalgae immobilized biochar introduced mangrove rhizosphere, offering physical protection through biochar's porous structure, mitigating tidal

salinity stress, facilitating nutrient release, thereby synergistically enhancing colonization efficiency microalgae, durability functions, capacity improve sediment environment.

4.2 Inhibition

ibrio angrove quaculture oupling ystem Mangrove regions frequently establish synergistic relationship aquaculture, particularly shrimp cultivation.

Vibriosis represents significant challenge aquaculture business, leading substantial economic losses *Vibrio* significant marine pathogen. pathogenicity intricately linked biofilm formation production virulence factors governed agent responsible decline marine aquatic products, deterioration mangrove roots, mortality seedlings Incorporating marine microalgae activity mangrove aquaculture systems offers sustainable approach controlling vibriosis aquaculture.

propose effect microalgae aquaculture systems realized through various pathways: .Direct release substances aquatic environment: microalgae continuously secrete metabolites activity during their growth.

These compounds diffuse aquaculture water, disrupting system *Vibrio* thereby inhibiting biofilm formation surfaces cultured organisms aquaculture facilities diminishing their virulence expression suggests microalgae serve source production active substances. .Microalgae microalgae combined bacteria additives: microalgae exhibiting activity serving carriers modulate bacterial activity function additives aquaculture species, enhancing their immunity directly inhibiting pathogenicity *Vibrio* intestinal tract surface these animals.

Despite scarcity research direct application microalgae exhibiting activity additives their effects aquatic organisms consuming these microalgae, prior studies demonstrated compounds derived marine organisms utilized additives suppress proliferation pathogenic bacteria within aquaculture systems, these compounds shown possess potential. application *Paratapes undulata* additive demonstrated marked improvement growth decrease mortality rates tilapia afflicted *Vibrio alginolyticus* modulate immunological response, augment antioxidant capacity, suppress pathogenicity *alginolyticus* polyphenols, sterols, fatty acids, other potential substances abundant *undulata* primary secondary metabolites marine microalgae Similarly, *Lactobacillus plantarum* strain, extracted lees, inhibit several *Vibrio* species vitro decrease mortality abalone infected *parahaemolyticus* vivo.

Marine microalgae carry bacterium, regulate release substances, exert antibacterial effects host' s cultivation *pumilus* medium enriched microalgae cyanobacterial biomass markedly inhibits biofilm development *hydrophila anguillarum* through extracellular products These studies offer robust evidence application microalgae microalgae-derived active compounds additives.

Enhance breeding environment: photosynthesis microalgae release oxygen improve redox state water sediment, thereby inhibiting growth biofilm formation

anaerobic facultative anaerobic Vibrio benefit microalgae strategy mangrove aquaculture coupling system ecological sustainability. contrast antibiotics chemical disinfectants, microalgae induce resistance pathogenic bacteria, contribute chemical contamination aquaculture environment aquatic products aligns trajectory sustainable aquaculture enhances quality safety aquatic goods.

Nonetheless, implementation

method

aquaculture settings encounters obstacles, including stability efficacy ingredients, large-scale production technology microalgae, persistence intricate aquaculture environments

4.3 Enhancing

anaerobic conditions sediment through photosynthetic oxygen release Mangrove typically exists anaerobic microanaerobic condition, which restricts healthy development mangrove plant roots creates conducive conditions survival reproduction numerous anaerobic facultative anaerobic pathogens anaerobic environment facilitates development persistence biofilm, complicating eradication harmful microorganisms. photosynthetic autotrophs, marine microalgae crucial ecological releasing oxygen during photosynthesis. incorporation benthic microalgae mangrove sediment water markedly enhance redox state sediment, thereby indirectly exerting effects inhibiting pathogenicity pathogenic bacteria. mechanism which microalgae facilitate photosynthetic oxygen release enhance sediment environment encompasses several processes: elevating dissolved oxygen levels through photosynthesis presence light, resulting oxygen production subsequent release surrounding water sediment, which inhibits proliferation anaerobic Vibrio Erwinia mangrove ecosystems disrupts biofilm formation altering redox potential convert anaerobic environment aerobic microaerobic thereby adversely affecting pathogenic bacteria reliant anaerobic metabolism interfering their promoting proliferation aerobic microorganisms, including certain bacteria activity, such marine actinomycetes Marinobacter mangrove ecosystems, or beneficial bacteria compete pathogenic bacteria resources niche, further mitigating pathogenicity these harmful organisms adaptation microalgae environmental conditions, including tide, salinity, light intensity, sediment type, considered utilizing benthic microalgae enhance mangrove sediment environment. crucial identify indigenous microalgae species capable thriving photosynthesizing intricate environment mangrove intertidal Moreover, biomass photosynthetic efficiency microalgae attain certain level exert substantial influence sediment environment These factors determine overall success failure utilizing microalgae-mediated strategies mangrove ecosystem conservation. discuss these aspects detail subsequent sections.

Overall, prospective strategy, approach directly limit dangerous bacteria effect substantially diminish likelihood disease outbreaks enhancing ecological envi-

ronment. comprehensive biological control

method

embodies concept Nature- Solutions

Strategy Dimension Target Problem Mechanism Action Expected Outcome infection Pseudomonas Xanthomonas

Direct Root Colonization

Vibriosis in shrimp /fish farming (*Vibrio* spp.).

Aquaculture Anaerobic pathogens sediment. Sediment Improvement

5. Challenges

erspectives Prevention Reduction virulence factors surfaces.

Reduced biofilm aquaculture species; Lower mortality; resistance.

Reduced biofilm aquaculture species; Lower mortality; resistance.

Inhibition anaerobic biofilm formation; Restoration benthic microbial balance.

Bio- Barrier: Colonization of roots. Symbiosis: Recruiting QQ bacteria.

Competition: Nutrient/ site competition.

Feed - Additive: Enhancing immunity;inhibition of vibrio in vivo Water Treatment:

Secreting QQ activity metabolites into water.

Photosynthesis: Increasing dissolved oxygen. Redox Shift:

Converting anaerobic aerobic/microaerobic environment.

Marine microalgae-mediated presents significant potential sustainable biological control approach safeguarding health mangrove ecosystems.

Nonetheless, numerous hurdles persist advancing technology laboratory research practical necessitating comprehensive research novel solutions. future, microalgae technology anticipated crucial Nature- Solutions, offering substantial support sustained health mangrove ecosystems.

5.1 Transitioning

laboratory field: adaptability alinity onditions mangrove habitat situated intertidal zone, characterized repeated variations significant salinity changes. dynamic challenging environment imposes stringent demands survival activity microalgae. active microalgae discovered under laboratory conditions perform

highly controlled environments, introduced field, their survival rate, growth rate, efficiency producing substances significantly affected.

Microalgae possess robust stress resistance acclimate intermittent wet-dry cycles, water erosion, variations light, extensive salinity fluctuations During tide, certain microalgae subjected atmospheric exposure, encountering dehydration intense radiation; conversely, tide, acclimate shear forces water nutritional dilution. salinity mangrove water bodies influenced tides, precipitation, river runoff, various other factors, resulting significant fluctuations freshwater salinity, necessitating microalgae possess tolerance.

Salinity fluctuations influence internal osmotic pressure metabolic microalgae, subsequently altering synthesis pathway secondary metabolites leading reduction active substance production.

Consequently, elucidating metabolic regulatory network microalgae response salinity variations essential enhancing their environmental adaptability genetic engineering optimization culture conditions. instance, certain studies examined influence bacteria marine sources biofilm contamination membrane bioreactors (MBR) under salinity stress potential salt-tolerant bacteria management plant diseases thereby offering reference implementation strategies environments fluctuating salinity.

Furthermore, sufficient microalgal biomass necessary field setting generate notable impact. successful colonization long-term survival microalgae mangrove roots present technical challenge.

Consequently, creating innovative microalgae delivery systems, immobilizing microalgae biocompatible materials enhance their stability efficacy environment crucial strategy effectively address issue.

Simultaneously, optimizing microalgae growing conditions pre-application mangrove ecosystem enhance biomass material production crucial precondition field application

5.2 Ensuring

ecological security: utilizing indigenous microalgae implementing biocontrol technique within natural ecosystem, ecological safety foremost concern.

introduction

non-native genetically engineered microalgal species

result

unforeseen consequences native biodiversity ecological equilibrium mangrove ecosystem.

Consequently, emphasis placed development implementation strateg utilizing local indigenous

microalgae. utilization indigenous microalgae offers numerous benefits: established prolonged coevolutionary relationship other organisms within mangrove ecosystem integral ecosystem, thereby reducing disruption original nutrient cycle, species interactions, while mitigating potential ecological invasion risks associated

introduction

non-native species Following long-term natural selection, indigenous microalgae become highly suited specific tidal, salinity, temperature, light, nutritional conditions mangroves, resulting superior survival rates functional stability their natural environment compared non-native species.

Furthermore, employing local microalgae successfully mitigate possible ecological risks associated foreign microalgae unknown pathogens toxic compounds detrimental non-target organisms achieve effective utilization local indigenous microalgae, essential conduct comprehensive biodiversity assessments screenings, isolate identify local microalgae species exhibiting activity mangrove ecosystems, further investigate their physiological ecological traits, mechanisms, interactions mangrove pathogenic bacteria plants.

5.3 Summary:

ature- olutions Marine microalgae-mediated novel biological control method, aligns seamlessly concept ature- olutions. prioritizes utilization improvement natural processes tackle social issues while delivering biodiversity advantages ecological services. microalgae strategy address mangrove diseases environmentally sustainable

methods

harnessing inherent biological functions microalgae, instead depending man-made chemicals. simultaneously diminishes bacterial virulence circumvents selective survival pressures responsible development antibiotic resistance. benefits strategy include: .Sustainability: microalgae renewable biological resources; their function depend finite chemical inputs, likely induce resistance pathogenic bacteria ensuring long-term sustainability Environmentally friendly:

Microalgae their metabolites typically biodegradable, accumulate environment, exert minimal impact non-target animals ecosystems.

Furthermore, photosynthesis microalgae enhances water quality sediment conditions, yielding supplementary ecological advantages Multifunctionality:

Microalgae exhibit effects secrete antimicrobial compounds, stimulate plant growth, function aquaculture feed, presenting diverse application values .Sys-

tematic protection: concurrently safeguarding mangrove plant roots co-cultured aquaculture organisms, microalgae strategy facilitate comprehensive health maintenance entire mangrove ecosystem.

Notwithstanding challenges, recent advancements biotechnology, genomics, ecological research provide optimism effect marine microalgae transition laboratory settings natural environments, emerging crucial instrument safeguarding health mangrove ecosystems.

Future research should concentrate high-throughput screening identification, developing efficient platforms rapid identification local indigenous microalgae their bioactive compounds mechanism

analysis

optimization, conducting in-depth examination molecular mechanisms microalgae optimizing enzymes bioactive substances through bioengineering field application technology development investigate colonization, survival, dispersal strategies microalgae complex environments; ecological assessment, performing comprehensive ecological assessment microalgae strategy; synergy other strategies, exploring interactions between microalgae other biological control ecological restoration approaches. persistent efforts regarding impact marine microalgae become important element managing health mangrove ecosystems, fostering harmonious cohabitation humans environment, establishing sustainable coastal ecological barrier. technology laboratory mangrove field applications. schematic illustrates transition stable, controlled laboratory conditions complex field environments mangrove intertidal zone.

Successful technology transfer hindered environmental challenges, including tidal fluctuation scour, extreme salinity variations, radiation dehydration, nutrient competition dilution.

These stress factors collectively reduce microalgal survival, growth, efficacy. mitigate these impacts facilitate Nature- Solutions (NBS) ecosystem health, proposed future directions include screening indigenous microalgae strains, optimization pre-application culture conditions, development advanced immobilization techniques. ultimate achieve sustainable effective biological control within vulnerable marine ecosystems.

6. Conclusion

conclusion, persistent infection caused aeruginosa other pathogenic bacteria through regulation biofilm formation clearly suggests marine microalgae-mediated offers indeed viable green biological control strategy maintenance mangrove ecosystem health.

analysis

paper indicates microalgae their metabolites effectively disrupt pathogenicity pathogenic bacteria through three primary mechanisms: enzymatic hydrolysis signaling molecules, competitive receptor binding, inhibition signaling molecule synthesis. circumventing significant drawbacks conventional chemical prevention treatment often resistance.

Within intricate ecosystem mangroves, microalgae-based strategy presents high-potential multi-faceted application framework: colonizing systems create protective barrier plants, obstructing disease transmission mangrove-aquaculture integrated systems, utilizing oxygen production photosynthesis fundamentally improve anaerobic microenvironment sediments.

These methodologies together effectively establish comprehensive ecological protection network, forming three-dimensional framework ecological preservation.

Nonetheless, advancing microalgae technology laboratory settings practical field application obstacles. regular tidal erosion significant salinity variations intertidal mangroves impose stringent demands environmental adaptation microalgae. extraction application native microalgae fundamental surmounting aforementioned environmental challenges, mitigating threat invasive species, guaranteeing ecological integrity. future, ature- olutions” research emphasis microalgae technology should transition towards high-throughput screening indigenous algal species, precise structural

analysis

active compounds, innovation colonization techniques intricate environments.

Through comprehensive integration multi-omics technology ecological engineering, function marine microalgae evolve fully developed application system, establishing effectively robust biosafety barrier sustainable advancement global mangrove coastal ecosystems.

Authorship contribution statement

Hongyi Su: Writing -original draft,Investigation,Visualization, Conceptualization.

Yizhi Huang: Writing -original draft,Investigation,Validation.

Zixuan Liang: Writing -review & editing,Visualization,Validation.

Declaration Competing Interest authors declare known competing financial interests personal relationships could appeared influence reported paper. availability available request.

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