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Investigating mangrove-human health relationships: A review of recently reported physiological benefits

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ABSTRACT

Ecosystems continue to experience degradation worldwide, with diminishing ecosystem services presenting unfavourable outlooks for all aspects of human wellbeing including health. To inform protective policies that safeguard both ecological and health benefits, syntheses of available knowledge are required especially for neglected ecosystems such as mangroves. However, reviews about relationships between mangroves and human health are rare.

This review identifies and categorizes evidence reported in the Web of Science database about health impacts of mangrove ecosystem goods and services. 96 papers were retained after application of exclusion criteria and filtration steps to results of database and bibliographical searches. Findings highlight most abundantly that bioactive extracts of mangrove sediment, plant, and plant associates are useful for the treatment of human ailments and infections. Also reported is the heavy and trace metal bioremediation capacity of mangroves ecosystems, with concomitant modulating effects on associated human health risks. Evidence of mangrove influence on human nutrition via fisheries and food production support services, either singularly or in conjunction with linked ecosystems is also offered. Finally, mangrove effects on the prevalence of causative agents, and therefore on the incidence and distribution of infectious diseases, are also presented.

Positive influences of mangroves on human health are implied via three of the four routes reported, which diminish with degradation and appreciate with proper ecosystem functioning. The undesirable links lie chiefly with higher infectious disease risk posed by mangroves, which requires further exploration regarding suspected ecological pathways available for limiting said risks. Other gaps identified are sparse information about in-vivo efficacy and safety of mangrove bioactive isolates, specific nutrient content and diversity associated with mangrove-supported food production outcomes, and the geographically limited nature of most findings.

Beyond economic value, health benefits of mangroves are significant and outweigh their disservices to humans. To ensure sustainable supply of the full complement of these benefits, they should be considered when designing ecosystems management regimes.

HIGHLIGHTS

- Web of Science search produced 96 papers assessing physiological health-related mangrove benefits
- Results sorted under pollution bioremediation, food provision, medicinal value, and disease/vector regulation services
- Assessments conducted and reported under a wide variety of methods, indicators, and measurement parameters
- Physiological health benefits were reported for most mangrove ecosystem services except for infectious disease risk
- Gaps lie with in-vivo potency of extracts, nutrient content of food products, and ecological routes to disease risk reduction

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Contents

1. Introduction

The World Health Organisation (WHO) takes a broad stance on what health entails, defining it as “a complete state of physical, mental and social wellbeing, and not merely the absence of disease of infirmity” [1]. Health is accordingly not guaranteed by a mere absence of disease, without the full complement of biological, psychological, and social factors. The Millennium Ecosystem Assessment [2] identifies major ecosystem services linked to attainment of health-promoting conditions as: climate regulation, water purification, food, wood and fibre, flood regulation, freshwater provision, fuel supply, and disease regulation. Lesser-impacting educational, recreational, spiritual, and aesthetic services are also cited. Holistic health can thus be derived from the direct or accrued impacts of services supplied by key ecosystems, including mangroves.

The MA catalysed growth in research and a greater appreciation of the need for protection, restoration, and conservation of ecosystems. Further, SDG3 of the UN Agenda 2030 [3] positions ‘good health and wellbeing’ alongside halting land and forest degradation (SDG 17) as targets that must be attained together for a sustainable future. Unfortunately, as evidence of health-related benefits of well-functioning ecosystems become better established, the academic space is simultaneously confronted with indications of rapid and widespread decline in the supply of ecosystem services. Anthropogenic interferences are compromising the abilities of many of the world's most vital ecosystems to provide life-supporting services [4–7]. With issues like climate change and increasing populations further exerting pressures on these ecosystems, there have a been growing calls for changes in policy direction, particularly, those that incorporate knowledge of the nature-health relationship [8,9]. A clear understanding of this relationship is however selectively scarce in the literature, especially for non-terrestrial ecosystems [10].

A cursory look at ecosystem assessments shows skewed attention on terrestrial ecosystems, leaving the mapping of ‘marine and coastal ecosystem services’ (MCES) at a distinct disadvantage [11]. This gap has been attributed partly to the limited availability of tools for pinpointing high-resolution and overt information relating to MCES [12,13]. A further inadequacy is the lack of a customised valuation system for MCES, many of which have relied on indicators and proxy ecosystem service data fine-tuned for terrestrial ecosystems [14,15]. Lack of robust biophysical measurement and social assessment regimes in the face of exploitation for rapid human advancement, have often favoured the demise of some critically threatened MCES ecosystems. This is especially true for mangroves, which have not only been designated as ‘wastelands’ historically, but also subjected to weak valuation mechanisms that have progressively favoured their loss [16]. The seeming advancement of human wellbeing in the face of rising ecosystem degradation [17] presents a further constraint in the establishment and communication of the direness of the degradation-wellbeing linkage. This signifies a need for comparative anlaysis of degraded versus intact mangrove causal associations with all wellbeing aspects including health, to facilitate policy enhancement in favour of ecosytem restoration and protection.

Mangrove ecosystems, found at the interface between terrestrial and marine ecosystems, and dominated by unique plant communities, are adapted to a variety of alterable conditions of substrate, oxygen level, salinity, and temperature. Assessments such as Duke et al. [18] outline how loss of a wide range of natural mangrove products and ecological services can limit human health (Fig. 1) and wellbeing. Alongside natural disruptive phenomena, anthropogenic interferences unfortunately continue to subject these specialised ecosystems to undue stress, leading to continued losses in cover [19,20].

Health-related mangrove literature however remains sparse and fragmented, in contrast with the situation regarding other terrestrial habitats and corals. The few mangrove reviews found have concentrated on ecological characteristics, economic value, impacts of environmental change on ecosystem resilience etc. (Table 1), with none focusing on human health links.

In addressing the highlighted knowledge gap, the objective of this systematic review is to outline current and potential relationships between mangrove ecosystem services and physiological human health, by answering the following research questions:

1. What are the most-commonly reported dimensions in the literature about non-economic mangrove connections to physical health?
2. How do mangrove ecological processes account for the pathways that exacerbate, limit, or eliminate threats to good health?
3. What are the impacts of mangrove ecosystem disturbances on the described health benefits, and where do outstanding gaps in knowledge lie.

Without the benefit of a definitive causality framework, recently observed and implicit linkages between physical health components and services from mangrove ecosystems are presented. The WHO definition of health is used to appraise the relevance of ecosystem services provided by mangroves to humans, as submitted by Duke et al. [18]. This approach does not attempt to attach strength or certainty to linkages that are drawn between physiological human health and mangrove ecosystem services. This review nonetheless provides some qualitative context regarding

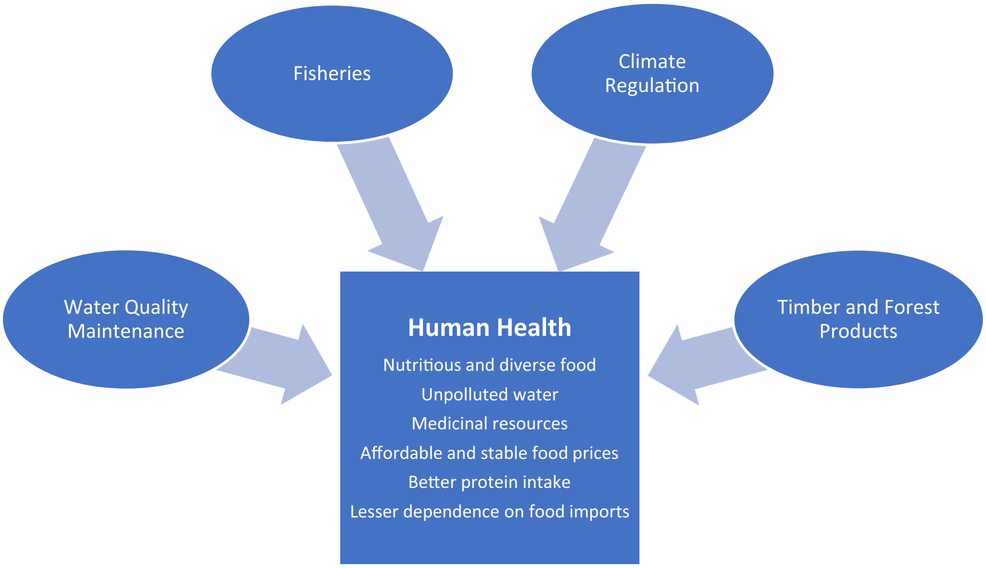

Fig. 1. Mangrove ecosystem goods and services and their human health impacts that are lost with ecosystem degradation.

Table 1
Sample collection of mangrove ecosystem reviews.

Ecological chemistry	(Che, 1999) (MacFarlane et al., 2003) (Defew et al., 2005; Lewis et al., 2011) [21–24]
Historical characteristics	(Walsh, 1974) (Hogarth, 2007) [25,26]
Habitat function	(Nagelkerken et al., 2008) [27]
Macrobenthos	(Lee, 2008) [28]
Economic value	(Rönnbäck, 1999) [19]
Medicinal uses	(Bandaranayake, 2002; Velmani et al., 2016; Thatoi et al., 2016) [29–31]
Nutrition	(Reef et al., 2010) [32]
Effects of oils and dispersants	(Thorhaug, 1989) (Burns et al., 1993) (Proffitt, 1997) (Hoff, 2002) [33–36]
Climate change	(McKee, 2004) (Gilman et al., 2008) [37,38]

what is noteworthy in decision and policy making around the mangrove-human health nexus. It highlights what ecosystem services are worth maximising in the design of mangrove conservation and restoration regimes, to boost concurrent delivery of health and environmental sustainability outcomes. It further highlights outstanding opportunities for further research to facilitate better precision in future syntheses. It is noteworthy that while restoration reinstates some ecological and biogeochemical functions of mangroves such as microbenthic faunal production and waste remediation to natural levels, the process can be both slow and unguaranteed [39]. For other functions such as heavy metal accumulation, characteristics restored are often equally comparable to natural mangroves. Altogether, these properties are however better than what is exhibited by degraded mangroves and unvegetated tidal flats [40], especially where multiple mangrove species are replanted.

2. Methodology

2.1. Literature search and selection criteria

This review relies on the 'Guidelines for Systematic Review in Conservation and Environmental Management' [41], as well as the PRISMA methodological guidelines for transparent reporting of systematic reviews [42]. It consists of a systematic and selective literature assessment on the results of a broad search of relevant content on health-related mangrove ecosystem services. Using the ISI Web of Science database, sets of comprehensive bibliographical searches were conducted using two sets of keywords: 'mangrove ecosystems' AND 'human health', or 'mangroves' AND 'human health', between the year 2000 to 31st July 2020. The year 2000 was chosen to include only recent and presumably more reliable knowledge around the search parameters, and to minimise inherent assumptions and uncertainty about mangrove ecosystem goods and services. This resulted in 512 peer-reviewed publications on human health issues related to mangrove ecosystems. After elimination of duplicates, the resultant collection of 324 was subjected to the filtration steps of abstracts, full texts, and bibliographical lists examination using the inclusion and exclusion criteria outlined in the next section. Retrievals made from bibliographical cues were retained irrespective of publication year, provided full-text examination deemed them substantially relevant to the review objectives. This combination of steps (Fig. 2) generated a final list of 96 papers subjected to further examination and qualitative analyses (See Supplementary Material for review references).

2.2. Exclusion criteria

The keyword searches returned a first set of literature that was filtered to exclude papers with a sole focus on ecosystem-related 'ecological risk assessments', and therefore had no direct relationship with 'human health'. Only English language publications reporting a primary assessment of mangrove ecosystem services related to physical health were included in this review. Publications that included mangroves as part of a more general assessment of 'nature', or services of various ecosystems and human wellbeing, were deemed to be beyond the purview of this review. Such papers were excluded because apart from time constraints, there was no justifiable means of mapping mangrove ecosystems alone to specific health outcomes. Also excluded were secondary and comparative assessments of previously established health-promoting links or properties. Publications included in previous mangrove ecosystem service reviews were retained if they had assessed health-related effects. Potential impacts are inferred for studies that assess health links at a purely experimental level without results verification in living systems or communities.

3. Results and discussion

Using the WHO definition of 'health' and the MEA delineations, food provisioning, regulation of water and sediment chemistry, provision of medicinal goods and disease regulation were identified as the key physiological health related mangrove ecosystem services contained in the retrieved records (Table 2). The presentation and discussion of results is

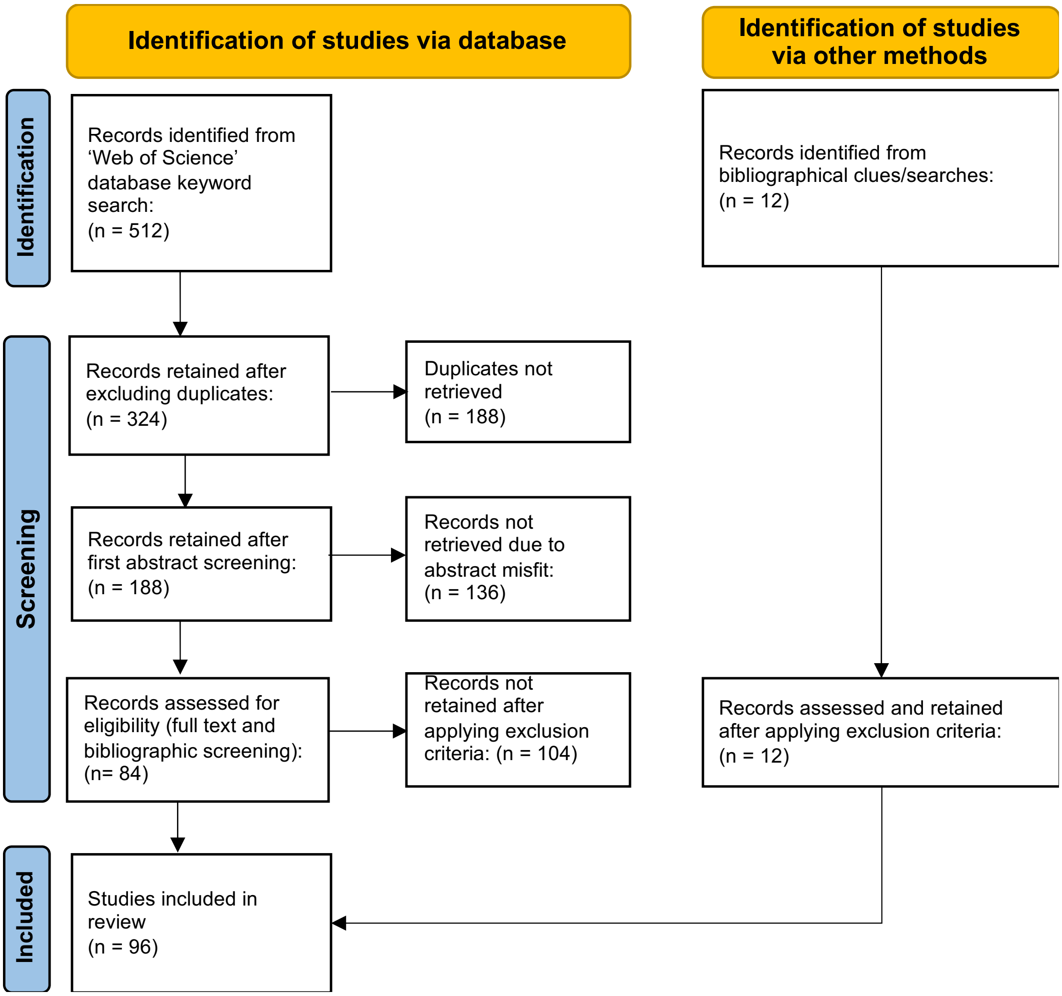

Fig. 2. PRISMA methodology flow diagram for collation of studies included in this review.

conducted under these categories, with commentary on some of the key findings and their ecological underpinnings.

Graphical representations of studies on relevant mangrove ecosystem services and their associated health impacts (observed, perceived or potential) were developed, highlighting representative papers that signalled positive, negative, or no conceivable links to human health. Finally, the unique properties and functions of mangrove ecosystems that facilitate health-related services are presented and discussed alongside the review findings.

3.1. Medicinal value of mangroves

Dependence on 'western medicine' has arguably become more widespread around the world, translating into a progressive decline in the reliance on indigenous knowledge on natural remedies which, for the most marginalised societies, tends to be otherwise invaluable. This shift could be precarious in the developing world, where risks of exposure to diseases, vectors, and nuisance insects persist due to combined effects of limited implementation of public health models and low socio-economic statuses. Given that a vast array of mangrove and mangal associates have long formed an integral part of folkloric disease management [43], their indispensable value in bridging this shortfall in the health delivery conversation is tangible. Cultural identities linked to mangrove can strengthen social relations in a manner that facilitates the generational transfer of ecological knowledge among mangrove users, some of which involve medicinal applications [44].

Accounts of indigenous applications of mangrove extracts for astringent, antipyretic, anti-haemorrhagic, analgesic, anti-inflammatory and

Table 2
Key physiological health-related mangrove ecosystem services identified in the review literature collection, using delineations of the MEA framework as a guide.

MEA Category	Mangrove Ecological Function	Mangrove Ecosystem Service/Disservice
Provisioning Services	Nutrient and biomass production and cycling for aquaculture, livestock, crop, and fisheries support	Influence on output of human food supply activities for nutritional support at subsistence and commercial scales (17 records)
	Phytochemical production by mangrove plant tissue and associates (e.g., endophytic fungi, actinobacteria etc)	Chemical isolates for medicinal and industrial application in human disease pathogen control and food preservation; bioactive compounds for alleviating human ailments (41 records)
Regulating Services	Bioremediation of pollutant constituents (organic and mineral) of waste discharges, oxygenation of dead zones	Attenuated impacts of heavy metal and hydrocarbon contamination of mangrove soil, food, and water sources (27 records)
	Regulation of abundance, spread and behaviour of pathogens and vectors of human disease through modification of biotic and abiotic habitat characteristics	Influence on the incidence and distribution of human pathogen-causing and vector mediated diseases (11 records)

anti-ulcer purposes are plentiful [29]. Numerous species of mangrove have also found traditional uses as sources of medicinal, pesticide and insecticide preparations, due to their richness in bioactive secondary metabolites [45]. However, some of these phytochemicals naturally occur in mangroves plants in their precursor form, selectively undergoing activation under pathogenic attack or tissue impairment [46]. To understand the specific medicinal potential of mangrove ecosystem resources, there have been numerous characterizations of chemical derivatives of leaf, stem, bark, root, and sediment samples that have revealed extensive medicinal usefulness. Some reviews of these accounts exist in literature [47–49].

3.1.1. Main findings

In the current review, types of mangrove resources from which the compounds were extracted fall into three major categories: plant and plant associates, actinobacteria and endophytic fungi. These plants and associates produce metabolites that help mangrove plants deal with pathogenic invasions [50,51], signalling potential antimicrobial applications. Flavonoids, phenols, terpenes, and aliphatic alcohols are a few of the types of bioactive compounds that have been widely identified as being responsible for the medicinal properties of mangrove resources. Generally, the species targeted for phytochemical assessments are those that have long-standing reputations within indigenous mangrove dwellers as being medicinally valuable.

Assays of bioactive mangrove-derived compounds captured in this review displayed antagonistic activity against diabetes mediating enzymes, diabetes mediating enzymes, and cancer cells as well as pathogenic microbes and food spoilage microorganisms (Fig. 3). Each assessment of isolates of mangroves or mangrove associates shows potential value for at least one pharmaceutical or food processing application. One key characteristic of said ‘bioactives’ is their increased efficacy when extracted using organic rather than aqueous solvents, suggesting potentially greater usefulness than currently observed under the predominantly aqueous traditional extraction pathways.

Antagonistic action was reported in a wide variety of proportions (Fig. 3). Antifungal ability was evident in only actinobacterial and endophytic fungal associates of mangal, whereas antipyretic and antioxidant action was seen in plant and plant associates only. Endophytic fungi and mangrove plants were the two sources of reported metabolites with anti-inflammatory abilities (Fig. 4).

Like others of the larger plant kingdom, mangrove extracts have been used for their anti-tumour abilities. They have been shown to possess the chemical compounds that exhibit cytotoxic effects on cancer cells, including phenylpropanoids and terpenoids [52]. The evidence supplied by Azman *et al.* and Hong *et al.* suggest that anticancer properties of mangrove extracts were demonstrated in the form of gene expression inhibition, cell cycle arrest and apoptosis of cancer cell lines. Whereas Azman *et al.* detected antagonistic action against cervical cancer cells of the ‘Ca Ski’ cell line, Hong et al. observed antitumor activity against colon cancer ‘116’ type cells as well as ‘Aurora Kinase A' protein inhibition, which ultimately leads to more effective apoptosis (immunological destruction) of cancer cells. These two studies were conducted on extracts of actinobacteria sourced from mangrove ecosystems, but similar results were reported for extracts of mangrove plants as well. Sari et al. for example, also observed induction of apoptosis and cell cycle alterations in colon cancer cell lines and concluded that the *Rhizophora* and *Ceriops* extracts tested hold promise for the development of anticancer agents. In Ramalingam and Rajaram, A549 lung cancer cells were found to be similarly susceptible to organic extracts of *Rhizophora spp.*

3.1.1.1. Antidiabetic action. Antidiabetic action of extracts of mangrove and mangrove associates reported in this review lies chiefly in inhibitory activity against enzymes (α-glucosidase, α-amylase) involved in glucose metabolism at the cellular level (see Nathiya and Mahalingam, Lopez *et al.*, Lopez *et al.*, 2018; Lopez *et al.*, 2019). Lopez *et al.*, (2018) in particular, highlight the outstanding therapeutic value of Panamanian mangroves, given the fact that 60% of the mangrove extracts studied showed α-glucosidase inhibitory activity. Work done by Ai *et al.* and Hong *et al.* alternatively described inhibition of another diabetes-related protein (tyrosine phosphatase 1B-PTP1B), representing about 3% of the investigated actinobacterial isolates in the latter study. One limitation, in respect of these inhibitory actions, lies in the fact that these studies were conducted in-vitro, which leaves the questions of toxicity and concomitant cell or tissue effects largely unanswered. The only exception was Ai *et al.*, who specifically concluded that the chief compound analysed demonstrates promise for diabetes treatment without toxic side effects. Taken together, the results of these assessments validate the traditional use of these mangrove derivatives against hyperglycaemia.

3.1.1.2. Antioxidant action. Mangrove ecosystems are characterised by extraordinary conditions of frequent inundation, anaerobic mud, and high salinity among others [53]. Due to these environmentally stressed conditions that mangrove plants are adapted to, they exhibit unique antioxidant mechanisms that enable them to scavenge free-radicals and protect the plants

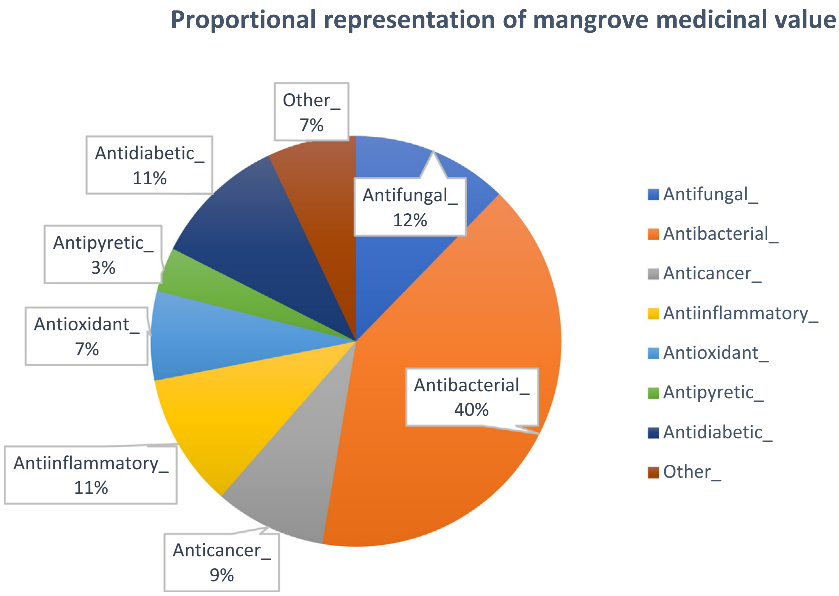

Fig. 3. Proportional representation of reported medicinal properties of mangrove bioactive compounds.

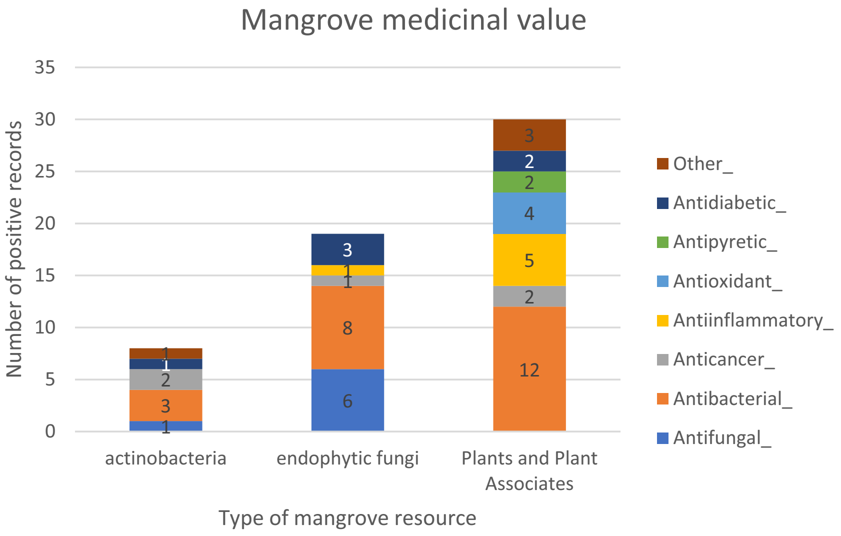

Fig. 4. Respective number of records reporting diverse biological activity for different mangrove resource types.

from destructive reactions [45]. This property is often transferred to their aqueous and organic extracts.

Suganthy *et al.*, Patra *et al.*, Hamzah *et al.*, and Islam *et al.* in this review allude that free-radical mopping ability of mangrove derivatives, which confers antioxidant properties, increases with increasing phenolic content. Such properties protect cells and tissues by averting the chain reactions that lead to oxidative stress and damage. For example, nitric oxide synthases, enzymes which produce the potentially oxidative cellular signalling nitric oxide, can be inhibited especially by methanolic stem and leaf phenol extracts especially of *Rhizophora, Avicennia, Bruguiera, Deris, Suaeda and Xylocarpus* spp. Chi *et al.* and Ravangpai *et al.* report of antioxidant action of this nature for mangrove endophytic fungi and seed extracts respectively. Chi *et al.* show that higher anti-inflammatory action is accompanied by lower cell viability for the isolates analysed, raising questions about tolerance levels and toxicity.

3.1.1.3. Anti-inflammatory action. Anti-inflammatory effects, expressed in the form of protection against complex biological responses to harmful stimuli (e.g., pathogenic attacks or injury) was reported in this present review, but to a lesser extent than antimicrobial action by Roome *et al.* and Shilpi *et al.* In Islam *et al.*, leaf and bark extracts of *Heretia fomes* mangrove demonstrated significant anti-inflammatory activity, although not as strong as diclofenac sodium anti-inflammatory drug. Barik *et al.*, in reporting on similar anti-inflammatory action of leaf extracts of *Bruguiera spp*, concluded that modulation of oxidative stress, coupled with arachidonic acid inflammatory cytokine inhibition, could be the mechanisms of action. The strongest evidence of anti-inflammatory potential is supplied by Eldeen *et al.*, with 75% - 96% inhibition of inflammatory enzymes reported for leaf and root extracts of same *Bruguiera spp,* including remarkable absence of associated cytotoxic effects.

3.1.1.4. Anti-microbial action. Strong and broad-spectrum antibacterial action, including against human pathogenic bacteria, has been previously attested for several mangrove species [29]. In the present review, antibacterial property was the most reported (40% of studies) for mangrove ecosystem secondary metabolites (Fig. 3). This antibacterial action was established against most human pathogenic microbes, such as faecal coliforms that cause gastroenteritis (e.g., *E. coli*), agents of food spoilage (e.g., *Streptococcus spp.*) and those responsible for urinary tract infections which affect over 50% of adults in their lifetime (see dos Santos *et al.* and Devi *et al.*). Simlai *et al.*, (2016) detected inhibitory properties in wood extracts of *Ceriops decandra* against 9 bacteria strains, 6 of which are pathogenic to humans. Likewise, Simlai *et al.* (2014) and Yompakdee *et al.* report on stable antagonistic activity against both gram-positive and gram-negative bacteria, indicating potential suitability of *Sonneratia caseolaris* extracts for pharmaceutical and food processing applications. The study by Buatong *et al.* revealed that up to 61% of the endophytic fungal isolates possess antimicrobial properties, including inhibitory action against *Candida albicans* fungus. Expectedly, the familiar and competent antibiotic *Penicillium spp* of fungi produced the most potent inhibitors of *Salmonella typhi* bacteria in the work done by Rossiana *et al.*

Few of the pathogens tested were strains that are multi-resistant to current antibiotics. One fungal extract analysed in Kjer *et al.*, and 50% of the studied actinobacterial extracts in Jiang *et al.* for example, exhibited significant broad spectrum antibacterial action, including against resistant strains. Apart from the intrinsic value of biodiversity in mangrove ecosystems, this signifies promise of novel drugs that could address the growing worldwide antibiotic resistance menace.

3.1.1.5. Other findings. Human and plant pathogenic viruses, such as those responsible for tobacco mosaic, HIV-AIDS, and hepatitis B, have in the past been described to be susceptible to mangrove plant extracts, particularly of *Rhizophora* spp. [54] (Premanathan *et al.*, 1999). This was not captured in any of the findings of this current review. A series of further suggested bioactivities reported in other appraisals, such as antifeedant, antiulcer, antifouling and nematocidal abilities [45] did not show up in the present review either. The least reported properties, collectively designated as 'other', were antiparasitic (against *Plasmodium spp.*, *Trypanosoma spp.*,) in Lopez *et al.*, 2015 and neuroprotective action described in Azman *et al.* for actinobacteria, plant and plant associates (Fig. 4). While not all chemical isolates analysed demonstrated bioactive properties, every paper reported at least one desirable health-promoting attribute of the mangrove-derived compounds assessed, as catalogued in Table 3.

3.2. Regulation of sediment and aquatic chemistry

A growing abundance of evidence confirm the adverse effects of anthropogenic chemicals on the ecological conditions of mangroves [55,56]. Bioaccumulation pathways and toxicity are also described in the literature [24] with regards to mangroves and their associated biota. Saenger *et al.*, [57] for example, detail how physical and biogeochemical barriers in mangrove ecosystems act as interventive mechanisms for contaminant filtration. Left unchecked, trace metals have the capacity to bioaccumulate in mangrove plant and fauna tissues, posing health risks to consumers in high concentrations. Although rarely studied in relation to mangrove ecosystems, mercury in the form of methyl mercury for instance, is crucial

Table 3
Medicinal properties of mangrove plants and mangrove associates reported in review papers.

Type of mangrove resource	Papers	Species	Purpose	Health-related benefits
Endophytic fungi	(Nurunnabi et al., 2018)	*Heritiera fomes*	Assessment of cultured fungal associates to validate use in folk medicine	Antibacterial activity demonstrated against *E. coli* for all organic extracts except for ethyl acetate derivative
	(Nathiya and Mahalingam, 2018; Chi et al., 2019)	*Avicennia marina, Acanthus ilicifolius, Rhizophora mucronata and Rhizophora apiculata*	Antidiabetic and anti-inflammatory activity evaluated	Anti-inflammatory, α-glucosidase and α-amylase inhibitor action demonstrated Varying cytotoxicity observed, indicating the safer option. The higher the enzymatic inhibition of nitric oxide synthase (i.e., anti-inflammatory activity), the lower the viability of treated cells.
	(Hamzah et al., 2018)	*Rhizophora mucronata*	Isolation and screening of 74 fungal associates from the leaf tissue	Antimicrobial activity against pathogenic bacteria exhibited by one, and free radical scavenging ability by another
	(Meng et al., 2015)	*Avicennia marina*	Analysis of antimicrobial and cytotoxic activity	Some antimicrobial activity detected
	(Zhang et al., 2019)	*Bruguiera gymnorrhiza*	Bioassay of metabolites of mangrove-derived endophytic fungi	Anti-microbial activity against human and aquatic bacteria as well as plant pathogenic fungi Mixed results. Inhibitory action against some but not others.
	(Kjer et al., 2009)	*Sonneratia alba*	Characterization of endophytic fungi extracts	Anti-bacterial and antifungal activity detected. Two novel compounds exhibited weak antibacterial activity against *staphylococcus aureus*. Another compound showed broad antimicrobial activity against several multidrug-resistant bacterial and fungal strains
	(Buatong et al., 2011)	Various	assessment of 150 isolates	Anti-bacterial and anti-fungal action produced by 63% of inhibitory compounds. Varied action against human pathogenic bacteria and *Candida albicans*, including broad spectrum
	(Rossiana et al., 2016)	*Rhizophora apiculata* *Bruguiera gymnorrhiza*	Assessment of antibacterial activity against *Salmonella typhi*	Anti-bacterial action exerted by isolated *Penicillium* spp. which had the most significant activity
	(Ai et al., 2014)	*Kandella candel*	Assessment of antimicrobial, anticancer and antidiabetic properties	Anti-cancer and anti-diabetic action. 2 isolates had cytotoxic activity against 10 human tumour cell lines 1 isolate had inhibitory action against two key enzymes targeted in treatment of diabetes
	(Ling et al., 2016)	Various, plus Mangrove sediment	Assessment of antimicrobial activity and heavy metal remediation potential	Antibacterial and antifungal activity strongly shown in 2 out of 12 isolates Maximum Heavy metals bio absorption by 2 species
	(Lopez et al., 2019)	*Laguncularia racemosa*	Assessment of α-glucosidase activity of *Zasmidium* spp. isolate	Anti-diabetic action. Strain has bioactive contents that have beneficial properties (91.3% inhibition) for diabetes control and human health
Actinobacteria	(Li et al., 2019)	Mangrove soil	To explore pharmaceutical potential	Antagonistic activity against selected bacteria by 54 isolates shown
	(Jiang et al., 2018)	*Avicennia marina* *Aegiceras corniculatum* *Kandelia obovota,* *Bruguiera gymnorrhiza,* and *Thespesia populnea*	Screening of endophytic actinobacteria	Promise of antibacterial activity exhibited by 31 out of 63 cultivable strains, including against some resistant pathogens
	(Azman et al., 2017)	*Mangrove Soil*	Extraction of bioactive compounds from 3 novel associates for antibacterial, anticancer, and neuroprotective activity	Bacteriostatic activity in all extracts Anticancer activity in 1 strain against cervical cancer cell lines Varied neuroprotective action demonstrated in 3 extracts
	(Hong et al., 2009)	Various	Isolation and characterization of actinomycetes from mangrove soil and plant material in China	Over 2000 isolates 20% - Human colon tumour cell inhibition 5% - Candida albicans inhibition 10% - *Staphylococcus aureus* inhibition 3% - Diabetes-related protein inhibition
Plants and Plant associates	(Ramalingam and Rajaram, 2018; Sari et al., 2018; Gopal et al., 2019)	*Rhizophora spp.*	Evaluation aqueous and organic leaf, stem, bark, and root extracts of plant species to verify antimicrobial, anti-inflammatory, anti-cancer and	Anti-microbial action in bark extracts particularly efficient against human pathogenic bacteria. Organic extracts (mainly methanolic or chloroform) are the most effective. Some excellent antioxidant activities. Apoptosis, gene expression inhibition and cell cycle arrest were observed in varying proportions in anticancer studies
	(Audah et al., 2018; Eldeen et al., 2019; Barik et al., 2016)	*Bruguiera spp.*	Used traditionally to treat burns, inflammatory lesions, high blood pressure, haemorrhage, and ulcers. Antimicrobial and anti-inflammatory assessments of root, wet and dry leaf extracts.	Anti-bacterial action detected. Ethanol extracts were most potent against *E. coli* and *S. aureus*. Wet leaf extracts had more efficient antimicrobial activity. Strong anti-inflammatory properties, including modulation of oxidative stress found in methanol extracts
	(dos Santos et al., 2010; Devi et al., 2014)	*Avicennia spp.*	Bioassays of leaf, root, and bark extracts for antimicrobial properties	Anti-microbial activity. Roots extracts most efficient, leaf extracts potent against pathogens that cause urinary tract infections which affect over 50% of humans in their lifetime

(continued on next page)

Table 3 (*continued*)

Type of mangrove resource	Papers	Species	Purpose	Health-related benefits
	(Simlai et al., 2014; Yompakdee et al., 2012)	*Sonneratia spp.*	Antimicrobial and anti-oxidative assessment of leaf, root, and bark extracts to understand folkloric use as astringent and antiseptic agent	Activity exhibited against both gram-positive and, mainly, gram-negative bacteria for the methanol extracts but not as significantly for others. Clinical, food-processing, and pharmaceutical potential established
	(Ravangpai et al., 2011; Hasan et al., 2019)	*Xylocarpus spp.*	Investigation of antinociceptic and anti-inflammatory properties to validate traditional use	Anti-inflammatory activity, due to inhibition of nitric oxide production by macrophages detected. Rare in-vivo demonstration of 49%–68% pain reduction and inhibition of inflammatory response.
	(D'Souza et al., 2010; Saad et al., 2011)	*Lumitzera spp.*	To investigate antimicrobial activities of organic extracts of plant	Antimicrobial activity detected against gram-positive bacteria, which increases with increased extract concentration No effective action against fungi and viruses
	(Bose and Bose, 2008; Wei et al., 2015)	*Acanthus ilicifolius*	Evaluation of organic leaf extracts to understand use in asthma and rheumatism treatment	Moderate to high antibacterial and antifungal activity, protective effect on liver tissue and therefore preservation of liver function. No inhibition of duck hepatitis B virus
	(Islam et al., 2020)	*Heritiera fomes*	Antioxidant and anti-inflammatory potential of *Heritiera fomes* bark extract assessed in comparison to diclofenac sodium and indomethacine	Significant antioxidant and anti-inflammatory activity present
	(Simlai et al., 2017)	*Deris trifoliata*	In-depth phytochemical assay of stem tissue	Stable antibacterial and antioxidant activity observed, especially for the methanolic extract, under varied pH and thermal conditions.
	(Simlai et al., 2016)	*Ceriops decandra*	Purification and characterization of wood extract	Inhibition of 9 micro-organisms, 6 of which are pathogenic.
	(Patra et al., 2011)	*Suaeda maritima*	In-vitro Investigation of antioxidant and antimicrobial actives of aqueous and organic extracts	Strong antioxidant properties, free-radical, metal, and nitrous oxide scavenging activity and ascorbic acid content in both leaf and stem extracts had. Selected organic extracts showed inhibitory activity against some pathogenetic bacteria, using amoxicillin as standard.
	(Roome et al., 2008)	*Aegiceras corniculatum*	To investigate traditional use for treating inflammatory diseases	Anti-inflammatory activity significantly shown In-vivo and in-vitro, validating traditional use
	(Lopez et al., 2015)	*Pelliciera rhizophorae*	Evaluation of species potential as source of bioactive compounds to validate traditional medicinal use in Panama	Antiparasitic activity against *Tripanosoma cruzi* and *Plasmodium falciparum* Better inhibition of α-glucosidase enzyme than anti-diabetic drug acarbose
	(Neamsuvan et al., 2015; Lopez et al., 2018; Suganthy et al., 2009)	Various	Evaluation of general medicinal use. Investigation of antiparasitic, anticancer, antimicrobial, free-radical scavenging, and hypoglycaemic properties of organic extracts	Widespread use identified, including for antipyretic purposes. Demonstration of varying degrees of antibacterial and antioxidant activity, which increases with increasing phenolic content. In one case, no antibacterial activity was demonstrated against 7 food-borne pathogens studied. In another instance, 60% showed alpha glucosidase inhibitory activity, suggesting presence of hypoglycaemic compounds. One species had moderate activity against *Plasmodium* falciparum. No extract showed anticancer activity

for its effects on neural development in humans [58]. While a few studies, such as Macfarlane [59] have probed the effects of mercury bioaccumulation on mangrove plant physiology and survival, very little work appears to have been done in terms of possible linkages to health of nearby dependent human populations.

The fine grains of mangrove sediments are known to sequester up to 22 trace metals, with copper, zinc and lead being the most reported [24,60]. For this reason, sediment chemical contaminants have often been assessed alongside that of water and biota, using different parameters, to ascertain bioconcentration dynamics and toxicological risk to health [23,61–63]. While mangroves are generally more tolerant of trace metals, they're more susceptible to oil spills. This is because oil spills interfere with pneumatophore activity, which hinges on sheer tree survival, as well as being the primary adaptation for detoxifying contaminants and excluding ions in the first place [64]. Organic chemicals such as petrochemicals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAH) concentrations in mangrove sediments have been studied for their neurological and carcinogenic toxicities and varying adverse biological effects in human populations. [65,66].

3.2.1. Main findings

3.2.1.1. Heavy and trace metal remediation. Mangrove roots act as barriers preventing free heavy metal movement to more sensitive parts such as leaves [67]. Concentrations of accumulated metal contaminants decrease from mangrove root to stem to leaves in that order [60]. Iron plaques formed by oxygen released via underground roots prevent excessive uptake of heavy metals into root cells. Coupled with the fact that physico-chemical properties of the typical mangal sedimentary environment traps trace metals in biologically unavailable form, heavy metal contamination can thus be effectively excluded from mangrove tissue. According to Kathiresan and Qasim [68], anoxic conditions of mangrove sediments enable the formation of metal sulphides and organic complexes that bind heavy metals and make them less bioavailable. Reduced bioavailability of heavy metals in the mangrove environment, resulting from the stated ecosystem processes, reduces the risk of bioaccumulation in edible micro and macro fauna of the mangrove food chains. Fig. 5 demonstrates the biochemical processes in mangal ecosystems that make them effective mediators of trace metal pollution, except for the most mobile forms such as Mn and Zn [67,69].

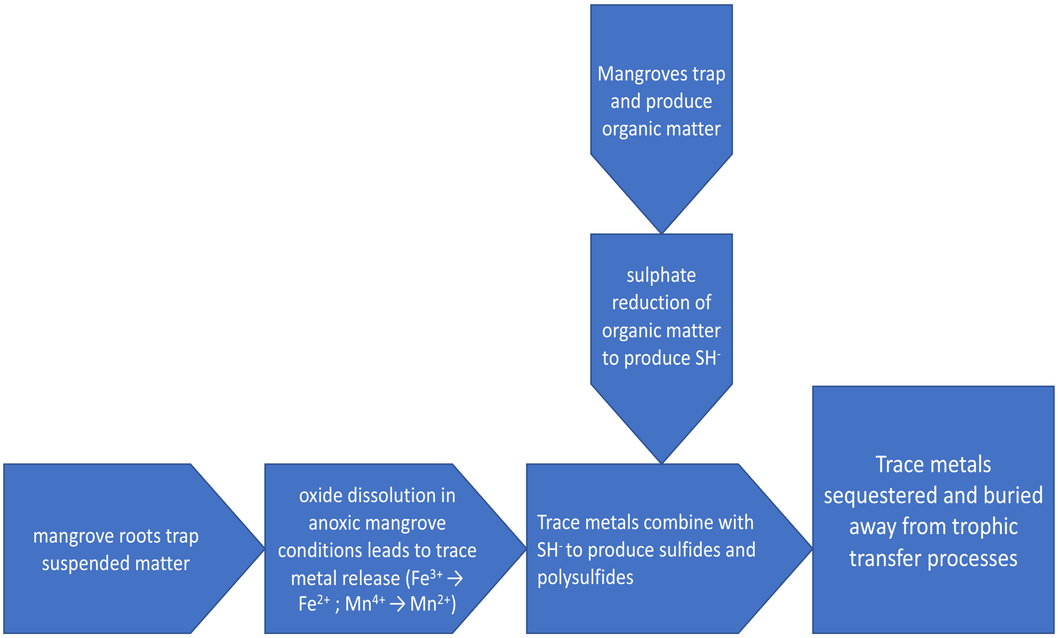

Fig. 5. Major anoxic metabolic processes in mangrove sediments involving metals.

Provided sediment binding capacity is not exceeded by excessive pollutant load, pollution intervening mechanisms of mangrove ecosystems can reduce ecological and health risks within the mangrove environment [70]. Disturbances in the form of climate-related precipitation, flooding, therefore salinity changes, which affect ecosystem integrity, can re-mobilize metal pollutants [71], with consequences for human health.

In the current review, heavy/trace metal pollution was discussed within the contexts of long-standing concern about pollutant accumulation within mangrove ecosystems, largely seen as waste reservoirs for surface, domestic and industrial run-off. In most cases, metal content of mangrove-sourced food was analysed as a proxy indicator of bioaccumulation magnitudes, and therefore the effectiveness of bioremediation processes of the ecosystem. The results indicate that despite regular subjection to heavy contaminant load, mangroves provide significant bioremediation services that minimise risks of heavy metals to human health.

Out of 27 papers pertaining to heavy and trace metal remediation captured within the current review (Fig. 6), only De *et al.* did not indicate some pollutant remediation effect of the mangrove ecosystem. The authors concluded that although occasional consumption posed no harm, 7 days of successive ingestion would be risky to health of consumers of fish from an Indian mangrove. Apart from that account, for every report of moderate or conditional pollution attenuation, there were two undeniably positive effects of mangroves on pollution outcomes for the aquatic or sediment environment.

Toxic enrichment from anthropogenic discharges into mangrove ecosystems have constituents including As, Hg, Cr, Pb etc. These heavy metal pollutants are readily ingested by intertidal organisms, some of which are consumed in abundance by humans. Liu *et al.* indicate that mangrove resources such as molluscs and fish could be potential heavy-metal hazards to humans consumers. Heavy metal ingestion via mangrove food consumption was the subject of the analysis conducted by Cheng and Yap. In this study, mangrove snails *Nerita lineata* soft tissue and surface sediments were analysed for As, Cd, Cu, Cr, Hg, Pb and Zn. Results indicated low ecological risk (PERI) values, which denote potential risk to consumers' health

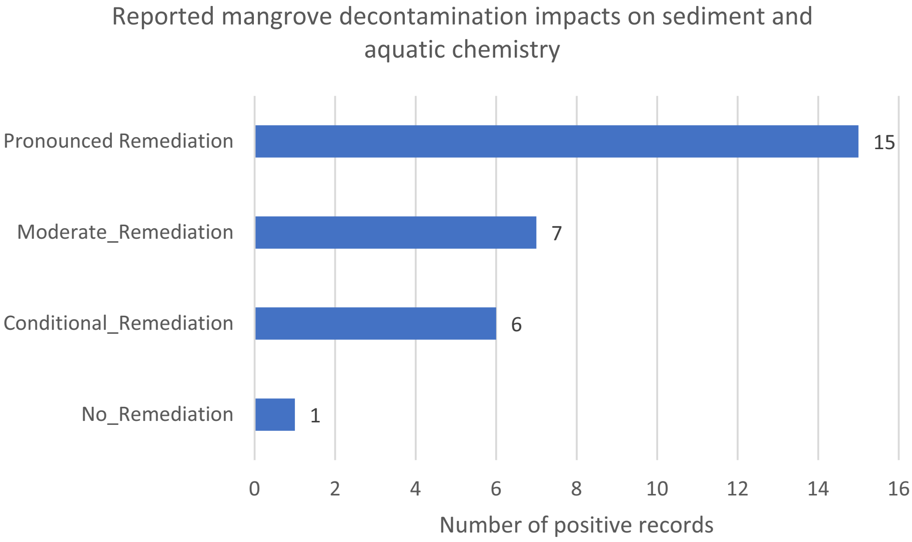

Fig. 6. Reported nature of pollution remediation effects of mangroves.

[72]. Estimated daily intake values were also generally lower than the reference dose (RfD-daily tolerance dose that poses no deleterious effects, [73]). Also, hazard quotients (THQ-ratio of dangerous vs. safe exposure levels) were less than 1 for low level consumers, which indicates no adverse health effects.

Some of the assessments, such as Aziz *et al.* and Wang, further suggest suitability of the mangrove ecosystem as a bioremediation tool for maintaining estuarine water quality, with natural and restored mangroves being observed to hold similar promise according to Li *et al.* (2016) and Boonsong *et al.* Peng *et al.* specify that this purifying function is extended to aquaculture ponds associated with mangroves, resulting in better self-purification of those synergistic systems. Two of the studies, (Nguyen *et al.* and Le *et al.*) cite elevated contaminant levels, and abnormally higher consumption of mangrove foods (especially of species higher up food chains), as the conditions that potentially undermine mangrove pollution mediating services. In a comparative assessment conducted by Li *et al.,* the unique causative role played by mangroves was demonstrated by decreasing Hg and Cu extraction capacity from mangrove to non-mangrove ecosystems subjected to similar pollutant levels. Additionally, Analuddin *et al.* establish how higher diversity of mangrove plants further amplifies this positive bioremediation service. Higher diversity of mangrove vegetation thus seems to promote more effective heavy metal exclusion, leading to better health outcomes for consumers of associated food products.

In the review by Lewis *et al.* [24], most of the studies on heavy metal detoxification activity of mangroves report on bioaccumulation in sediments, roots, and leaves; with the salt glands of leaves cited as major excretory pathways. Thus, mangroves can filter out some toxic materials from reaching marine species, including fisheries used as food. Some studies in this review such as Naidoo *et al.* which report similar results, however, indicate that mangroves may not necessarily be ideal phytoremediators, due to them not being comparatively hyper accumulators of heavy metals. The writers further assert that sequestered elements are eventually released into the environment through decay of dead plant matter. Metal-dependent differences in results are also likely, although not specifically investigated in this review.

3.2.1.2. Hydrocarbon (organic) pollutant control. Mineral nutrients like nitrogen and phosphorus are readily absorbed in mangrove topsoil, where they could then be metabolised by microbe communities, with phosphorus being more readily absorbed from wastewater than nitrogen (Tam and Wong, 1995). On the other hand, patterns of water flow via the mangrove ecosystem, which affect both flushing rates and residence time, determine the tolerance of mangal for organic pollutants. Recovery of mangrove ecosystems from oil pollution tends to happen more slowly, if at all. The effects of an oil spilling a mangrove area in Brazil for example, were not overturned until after a decade (see Lamparelli *et al.*).

Urban run-off, oil spills, industrial effluents and atmospheric pollutants are sources of toxic hydrocarbons that end up in mangrove ecosystems [74]. Mangrove response to PAHs has remained a curious interest for researchers due to impacts that include plant cell damage, and therefore growth reduction and mortality, morphological and physiological damage, and photosynthetic interference [75]. Some species of mangrove plants, such as *A. marina* and *R. mucronata*, which develop pneumatophores with wide sediment-root interface, may suffer consequences of PAH accumulation in root tissue. Apart from contributing to tree death, PAHs have also been implicated in health problems in nearby terrestrial and aquatic communities through food web transfers [76].

One paper captured in this review, Aziz., studied the mangrove ecosystem supported co-metabolism process that transforms toxic PAH contaminants into non-toxic forms through microbial action. Analysing a consortium of bacterial isolates from Malaysian mangrove sediments, the researchers probed the bioremediation effects of biodegradation of Benzo-a-Pyrene (BaP), an organic PAH with carcinogenic and endocrine disruption competence. Their conclusions suggest that the analysed collection of mangrove microorganisms is effective at biologically degrading benzopyrene PAHs under the unique saline conditions of the mangrove environment, especially at the optimal temperature of 30 °C typical of tropical regions. Tropical mangrove ecosystems thus, in the long term, support the ecological processes which potentially assuage the harmful health risks associated with widespread and persistent PAH contaminants like benzopyrenes.

Santos *et al.* on the other hand focused on PCB remediation in a Brazilian mangrove ecosystem, where no significant health risks were associated with consumption of exposed fish and shellfish. Furthermore, the authors opined that anthropogenic PCB contamination levels within mangrove bays investigated were markedly and comparatively lower than that of other non-tropical bays. This indicates how the biota and seafood of the mangrove environment in that location pose less of a risk to human health than in other regions. Similar results are reported in Bodin *et al.* (Table 4).

3.3. Mangroves and human nutrition

The main links between mangrove ecosystems and the provision of goods that support human nutrition, can be found in the combined mediation of aggravated bioaccumulation of harmful substances, and the habitat support services for fisheries. High productivity of mangroves ecosystems, which translates into energy for detritus-based food chains, benefits biomass and nutrient build up mechanisms in the ecosystem. Finally, as pointed out by Beck *et al.* [77] and Lee [78], mangroves provide conducive aquaculture conditions, critical nursery and retention grounds for fisheries larvae, as well as predation refuge for their juvenile forms. By helping fisheries populations to flourish, these mechanisms ensure that the nutritional needs of consumers including humans higher up the food chain, are met.

Mangrove fungi and bacteria are responsible for the decomposition processes that help to achieve high dissolved organic matter content in otherwise low-nutrient tropical waters, to the benefit of fisheries. According to Kathiresan and Bingham [67], greater inundation and feeding activities of invertebrates are some conditions that facilitate faster litter decomposition. Mangrove detritus appears to make more of a localised contribution to food webs, with its importance being probably greater as a microbial substrate than as a direct food source [79]. These unique services together, under optimal conditions, would eventually enable protein nutritional needs to be met.

Although the causal importance of mangroves in shoring up nurseries support functions remains contested [27,80–82], the connectivity of marine ecosystems to mangroves has been established as a key booster of overall fisheries productivity. Alternatively put, while the evidence does not necessarily point to mangroves being the sole backbone of associated fisheries productivity [83], as part of a wider matrix of well-connected adjacent ecosystems, they exert an undeniably desirable effect. Water pollution/sediment regulation, storm protection and fisheries habitat support etc., all depend on interactions between different marine ecosystems to varying degrees. For example, mangrove shelter provision function for juvenile fish species, may be more significant if nearby reefs are in a position to act as reproductive habitats. The two ecosystems can thus be seen as an essentially collaborative mechanism for successful completion of fisheries life cycles. By filtering pollutants in waste discharges, mangroves protect coastal communities as well as nearby coral reefs. Reefs, in turn, protect coasts by buffering oceanic waves and currents. Conservation efforts should thus ideally be extended to include all interconnected ecosystems, rather than being limited to solo mangroves.

3.3.1. Main findings

In the current review, 80% of the captured articles allude to some positive influence of mangrove presence on fisheries yields. In Barbier *et al.* some varied evidence shows nursery and breeding habitat functions being more pronounced at the seaward fringe than the inland portions of mangrove ecosystems. Competent connectivity between marine ecosystems (e.g., mangroves, saltmarshes, seagrass meadows, reefs etc) is, however, essential for the nutrient and material fluxes that yield bumper fisheries. Furthermore, Blaber concluded that over a 10-year period, mangroves supplied

Table 4
Pollution mediating action of mangrove ecosystems studied in review papers.

Paper(S)	Location	Purpose & target(s) of analysis	Health-related bioremediation findings
(RUMISHA ET AL., 2016)	Tanzania	Trace metals in 60 sediment and 160 giant tiger prawn samples to document distribution and potential threat to mangrove fauna and public health	As, Cd, and Hg present moderate risks to fauna. High levels of Cu, Fe and Zn were observed in prawns. Level of the non-essential Cd, Hg, and Pb did not exceed maximum allowed levels for human consumption.
(ANALUDDIN ET AL., 2017)	Sulawesi, Indonesia	Role of mangroves as a biofilter of heavy metals	Variety of trends in translocation and bioaccumulation factors. High mangrove plant diversity ensures health and productivity of coastal zones
(DE VALCK AND ROLFE, 2018)	Great Barrier Reef, Australia	Estimation of loss of benefits to society resulting from water quality reduction, influence of pollutants on ecosystem services of mangroves, seagrass, and coral reefs	Provisioning, regulating, and supporting ecosystem services from mangroves are crucial to well-being. Failing to meet Government's water quality targets by 1% would result in losses between AU$22 k/year and AU$6.9 M/year depending on the industry
(LING ET AL., 2016)	Malaysia	Characterization of plant and soil endophytic fungi and their antimicrobial production and bioremediation potential for heavy metals (Cu and Zn)	Mangrove endophytic fungi produce bioactive compounds and have promising potential for the purification of heavy metal-contaminated wastewater
(NAIDOO ET AL., 2014)	South Africa	Soil retention and root ultrafiltration capacity to exclude trace metals via leaf salt glands of *Avicennia marina*	Salt glands of this mangrove species contribute to eliminating at least part of physiologically essential trace metals if taken up in excess
(PENG ET AL., 2013)	South China	Evaluation of combined mangrove conservation and aquaculture targets via assessment of water quality impacts of Integrated Mangrove Aquaculture System (IMAS)	Aquaculture ponds can become self-purifying through nutrient uptake by the mangrove, increasing harvests of some mangrove-dependent species increased by over 10%
(TAN ET AL., 2018)	China	Choice experiment to value the environmental improvements in coastal wetland restoration	People valued positive benefits of coastal wetland restoration, particularly water quality improvement potential. The mangrove area had the highest marginal 'willingness to pay' value.
(VAN OUDENHOVEN ET AL., 2015)	Java, Indonesia	Effects of different management regimes on mangrove ecosystem services (food, raw materials, coastal protection, carbon sequestration, water purification, nursery, and nature-based recreation)	Natural mangroves scored highest for most services, except for food
(WANG ET AL., 2017)	China	Evaluation of ecological service value of the mangrove forest using a market value method, an ecological value method and a carbon tax method	The indirect value of disturbance regulation, gas regulation, water purification, habitat function and culture research reached 14,719,000 CNY/a, with a ratio of 91.4%
(WANG ET AL., 2010)	China	Measurement of seasonal changes in water quality for samples taken at various distances from shallow water across mudflat to mangroves	Results support the hypothesis that the maintenance of estuarine water quality by mangroves occurs during flood periods
(BORRELL ET AL., 2016)	Bangladesh	Zn, Cu, Cr, Hg, Pb, Cd and As levels in 14 plant and animal species from mangrove forests used for food, were analysed for trace element transfer through the food chain	Fish and crustaceans were deemed safe for consumption by international standards, except for one species of each, which had concerning levels of Cr and Cd; and, Zn, respectively
(BODIN ET AL., 2013)	Senegal	Inorganic sediment and mollusc contamination in mangrove ecosystems	Strong differences in trace metal bioavailability and bioaccumulation, but levels were below threshold limits for 'adverse biological effects'
(LI ET AL., 2017B)	China	Heavy metal analysis of water, sediments, and edible molluscs from mangrove wetland	Varied bioaccumulation abilities in edible molluscs, sediment levels of Cd and Zn were lower than safety threshold, THQ show potential risk to consumers, but no harmful effects at daily intake quantities
(LI ET AL., 2016)	Shenzhen, China	Core natural mangrove sediment analysis to investigate mangrove influence on heavy metal accumulation and storage	Hg and Cu accumulation competence decreased from natural to restored mangrove, and then again to mud flat, indicating mangrove influence in heavy metal exclusion from aquatic environment
(MARTINEZ-SALCIDO ET AL., 2018)	California, USA	Hg-related human health risk from muscle and liver analysis of edible mangrove lagoons fish	None of the fish had Hg THQ that was risky to human health
(NGUYEN ET AL., 2019)	Vietnam	Assessment of distribution of Fe, Mn, Cu, Co, Ni Cr, As in tissues of mangrove plants and edible snail.	Level of contamination, sediment geochemistry and specific specie requirements influence tissue accumulation. Fe, Mn, and Cu most dominant in snail tissue; As high due to snail uptake and metabolization capacity
(AZIZ ET AL., 2018)	Malaysia	Benzo pyrene (PAH) digestion potential investigated for a consortium of mangrove sediment bacterial isolates	Natural biodegradation activity confirmed, indicating capacity for use in seawater bioremediation to reduce human health risks.
(BODIN ET AL., 2011)	Senegal	PCB concentrations in sediments, bivalves and gastropods examined for their human health risk	Concentrations from various assays showed no potential human health risk form shellfish consumption
(BOONSONG ET AL., 2003)	Thailand	Planted *Rhizophora, Avicennia Bruguiera and Ceriops* mangrove plant species evaluated for their wastewater purification capabilities	Constructed mangrove wetlands can attenuate wastewater pollution risk in a similar way as natural mangroves
(CHENG AND YAP, 2015)	Malaysia	Edible mangrove snails *Nerita lineata* soft tissue and surface sediments analysed for As, Cd, Cu, Cr, Hg, Pb, Zn	Low ecological risk (PERI values). Estimated daily intake values lower than the RfD, THQ less than 1 for low level consumers.
(COSTA ET AL., 2018)	Brazil	Individual consumption health risk assessment of Pb in edible mangrove crab *Goniopsis cruentata*	THQ less that 1, indicating negligible risk to human health through use as food
(DE ET AL., 2010)	India	Levels of Cu, Zn, Ni, Cd, Cr and Pb in edible fish assessed for a mangrove dominated estuary	PTWI per kg body weight values were marginally high, posing a health risk in 7-day successive consumption scenario
(KANHAI ET AL., 2014)	Trinidad and Tobago	Presence and potential impact of Cd, Cr, Cu, Ni, Pb and Zn in mangrove sediments and oysters	Low and minimum ecological risk based on Canadian sediment quality guidelines. Zn levels potentially unsafe to health of oyster consumers
(LE ET AL., 2017)	Malaysia	Hg bioaccumulation assessment in edible finfish for human health risk	Health concern for carnivorous species consumption; overall trans-trophic assessments indicate generally low risk based on PTWI
(LI ET AL., 2017A)	Dongchaigang, China	Seawater, sediment, and mollusc heavy metal levels assessed for health risk	Only Zn and Cd levels low in sediments, heavy metal contamination of molluscs high, although THQ suggests no harmful effects on humans
(SANTOS ET AL., 2020)	Brazil	Examination of mangrove shellfish for PCB contamination	5 out of 12 species showed PCB presence, but levels lower than other regions around the world. No risk to human health through consumption as food.
(SHI ET AL., 2020)	Shenzhen, China	Assessment of distribution, pollution levels and human health risks in urban mangrove sediments	Levels highest in locations closest to point source discharges, little adverse public health risk from exposure to Hg

protective functions that inured to the benefit of fisheries in estuaries. The abundance of more juvenile than adult fish in mangrove creeks further supports the nursery function of mangrove habitats according to Gadjzik *et al.* The advocacy by Bell *et al.* for use of mangrove expansion as a climate change adaptive measure in dealing with food insecurity thus seems valid.

Binh *et al.* and Rajendran and Kathiresan collectively showed how shrimp aquaculture productivity could experience between 30% and 50% productivity increase when associated with mangroves, leading to greater yields and economic returns. Furthermore, they demonstrate how shrimp farm effluents in turn promote mangrove plant growth due to their nutrient richness. Information on mangrove oysters, which serve as a valuable food source, suggests that mangroves facilitate the ideal conditions that promote oyster and oyster bed production. This is attributable primarily to the adaptation of juvenile forms of oysters (spat) to the tidal regimes of mangroves, which enables accelerated growth because of intermittent exposure to air [68]. Results from Peng *et al.* show a 10% increase in aquaculture yield when a degraded mangrove site was replanted for the purpose. Mangrove litter reportedly contributed nearly 30% to the diet of the cultured fisheries, lending further credence to the findings of earlier studies by Binh *et al.* [40] and Rajendran and Kathiresan [84].

Toxicity from environmental catastrophes such as oil spills engenders stunted growth and leaf deformities of plants, tree die-offs and associated impacts on various macrofauna within mangrove ecosystems [85]. Large scale lethalities and migrations within mussel, oyster and crab populations are reported in other older literature, in connection to disruptive oil spill events within mangrove ecosystems [86–89]. A significant nutritional toll could be taken on the health of individuals who rely on these invertebrates for food. In Ngoile and Shunula, local commercial fish species caught with movable traps in Zanzibar were found to be associated with mangrove vegetation, with certain species such as the rabbit fish *Siganus spp* being the most abundant. One mollusc (*Pyzarus spp*) was found only in the mangroves. Particularly for edible shellfish that are specially adapted to mangrove ecosystems alone, the resultant impacts of toxicities and catastrophic ecological disturbances could be grave for consumers.

Rahman *et al.*, Mandal *et al.* and Primavera comment on mangrove support for grazing food chains, livestock, and honey production. The model presented by Mandal *et al.*, who sought to explain the exact reason for overexploitation-related decline in fish populations, depict the role of mangroves in maintaining a balance between the detritus and grazing food chains. Additionally identified in this collection of research, is a linkage between a reduced water purification functions in degraded mangroves, and a decline in food crop production yields. In Primavera, increased brackish water shrimp farming led to progressive mangrove loss, with concomitant deterioration of coastal water quality and domestic food crop decline. While fisheries, a contributor to human nutrition, was the benefit of highest value in the assessment by Rahman *et al.*, honey production and fodder for livestock were the second and third most valued mangrove contributors to wellbeing along the Bangladeshi coast. Identification of the relevance of honey corresponds with the widely held knowledge about honeybees travelling long distances to forage in mangroves according to seasonal preferences [90,91].

Indications from findings of the present review support recognition by mangrove dwellers, of the importance of the ecosystem in safeguarding the livelihood and nutritional gains derived from fisheries (Walton *et al.* and Rahman *et al.* in Table 5). Because of this belief, respondents in the study conducted by Martin *et al.* express willingness to relocate to mangrove areas as a coping strategy to address dwindling fisheries (Table 5).

3.4. Diseases, vectors, and mangroves

Waters of bays and estuaries, where mangroves typically thrive, tend to naturally support, or receive microbial populations of both natural and anthropogenic waste origins. Grisi *et al.* [92] demonstrate how pathogenic bacteria end up in the estuarine environment through discharges and land drainage. Alongside the presence of indigenous bacteria with pathogenic abilities, the microbial load of waste discharges into estuarine mangrove environments could pose significant public health concerns. Interestingly, as revealed by Penha-Lopes *et al.* [93], monitoring and assessment of this risk is not prominent in the academic space.

Enteric pathogens like *E. coli*, *Vibrio spp* and *Salmonella spp*., agents of gastroenteric illness in humans, enter the aquatic environment via faecally contaminated domestic waste discharges, where they effectively compete with and knock out other microbes [94,95]. The prevalence of *Salmonella* in mangrove-sourced food species for example, has been documented for food items including fish, crabs, and turtle meat [92,96,97]. Listeriosis, another human infection of substantial health consequence especially in pregnant women, is caused by *Listeria spp* of bacteria. Coastal waters are known to harbour strains of *Listeria*, particularly owing to their tolerance and preference for higher salt load and organic matter content respectively. For this reason, studies have reported *Listeria* contamination of water, fish, sediments, and shellfish harvested from coastal ecosystems [98,99]. The ability of human pathogenic bacteria to survive in mangrove ecosystems is derived from tolerance of wide ranges of pH, salinity, turbidity, and other stress agents. The volumes of freshwater deposits, ocean currents and tidal action etc., characterizing the estuarine environment, regulate the nature of contaminant dispersal and bioaccumulation in the food chain.

Hundreds of insect species are associated with mangrove ecosystems, although most tend to be temporary residents, with lifecycles that stretch into other habitats [100]. A number of these are of public health importance due to their roles as prolific vectors of human diseases. Although some of these vectors (e.g., mosquitoes and tsetse flies) can thrive in a range of habitats, their preference for wetland ecosystems is due to the aquatic-dependent aspects of their life cycles. Immature stages of mosquitoes for example, although prevalent in terrestrial environments, are better supported by aquatic and semi-aquatic ecosystems. For this reason, the disease risk posed by vector insects have been studied using a multidisciplinary approach that takes ecosystems and their ecological processes into account [101].

3.4.1. Main findings

3.4.1.1. Pathogenic microbes. Two out of 11 papers captured in this review (Fig. 7) focused on pathogenic microbes within mangrove-linked aquaculture ponds and on bivalves used as food sources (Gonzalez et al. and Ghaderpour *et al.* Both arrived at similar conclusions, which highlight the risks to health of human consumers (Table 6). This negative health risk lies in the potential transmission of food-borne gastroenteritis, signalling an inability of mangrove ecosystems to essentially mediate the impacts of coliform contamination.

3.4.1.2. Vector organisms. Wetland management for human health benefits previously consisted of drainage to minimise mosquito proliferation [102]. However, Thiere *et al.* [103] demonstrate how hitherto nuisance wetlands are now being recognised for their beneficial ecosystem services. It is therefore important to manage negative risks in ways that preserve these beneficial ecosystem services.

Crustacean burrows and tree holes (e.g., in *Avicennia spp.*) are ideal breeding locations for mosquitoes, which act as vectors of several vertebrate pathogens, and can occur in high numbers and diversity within mangal. The predatory action of larvivorous fish supplies a valuable biological control on mosquito oviposition. Therefore, fisheries supporting services of mangrove ecosystems tend to provide an indirect check on vector behaviour that could ultimately deliver an additional public health benefit. This aligns with evidence from Ritchie and Laidlaw-Bell [104] of lower populations of mosquitoes observed in mangrove ecosystems with high fish densities.

In this review, there was a diverse mix of motivations for studying vectors within mangrove ecosystems. Freiss describes historical perspectives dating back to the 19th century, in an account where up to 60% of respondents upheld the notion of mangrove forests being vector-borne disease reservoirs. Similar perceptions are thought to have fed into the legacy importance of mangroves for tropical peoples,

Table 5
Human nutrition support services of mangrove ecosystems reported in the review collection.

Authors	Description	Nutritional Health Support Links	Location
(Aburto-Oropeza et al., 2008)	To demonstrate the positive relationship between mangrove abundance at the water fringes, and fisheries landings	Mangrove-related fish and crabs account of up to 32% of small-scale fisheries landings. Destruction of mangroves has strong economic impacts on fishing communities and on food production in the region	Gulf of California
(Bell et al., 2018)	Exploration of adaptive strategies for maintaining food security in the face of climate change impacts on mangroves and seagrass habitats	Gap emerging between sustainable harvest practices and quantity of fish required for good nutrition. To optimize this gap, the landward expansion of mangrove communities and the maintenance of structural complexity of its associated fisheries habitats is suggested, among other strategies.	Pacific islands
(Blaber, 2013)	10-year review of fishes and fisheries in tropical estuarine environments	Neglected research issue of protective function that estuaries and mangroves provide for fisheries leads to expansion in popularity for restorative initiatives	Various
(Gajdzik et al., 2014)	Investigation of presumed nursery function of mangroves for ichthyofauna	Juvenile forms of food species more abundant in the mangrove creek than adults	East Africa (Kenya)
(Granek et al., 2009)	Examination of mangrove organic matter (OM) contribution to nutrient availability in coral reefs	Mangrove nutrient contribution decrease with increasing distance from the shore. Up to 57% of OM to sessile invertebrates, which play key roles in reef community structure, is supplied by mangroves	Panama
(Heithaus et al., 2011)	Examination of trophic structure within habitat types associated with fringe mangroves	No indication that mangrove productivity directly supports local fish populations	Western Australia
(Igulu et al., 2013)	Holistic exploration (modelling) of reliance of fish on mangroves as feeding habitat at multiple ecological levels	Two end-member mixing model showed 12–72% degree of fish reliance on mangrove food sources. High fisheries productivity of mangroves appears to be supported by food sources from adjacent habitats, indicating that ecosystem connectivity is crucial	Global
(Jinks et al., 2020)	Sampling of species close to urbanization to estimate trophic contribution of key primary producers to regional fisheries	Conservation of mangroves and phragmites would sustain fisheries production, as 6–70% of OM originate from wetland plants and underpin fisheries food webs	Eastern Australia
(Mandal et al., 2012)	Construction of holistic model of nutrient source to grazing to investigate cause of gradual decline in fish populations	Mangrove litter biomass plays major role in maintaining detritus and grazing food chains. Afforestation required to maintain ecological balance	West Bengal, India
(Martin et al., 2018)	To understand pressures faced by communities relocated due to environmental change	Climate change impacts identified as negatively affecting supply of marine and terrestrial foods. Relocation further inland and planting mangroves are preferred management/coping strategies	Yadua Island, Fiji
(Ngoile and Shunula, 1992)	Exploration of the status and exploitation of mangroves and associated fisheries	Mangrove wood utilised for charcoal, lime, and salt production. Fish species locally used as food were found to be bulk components of catches from water adjacent to mangroves. A particular mollusc species, used significantly as food and bait, was found only in mangroves.	Pemba Island, Zanzibar
(Peng et al., 2013)	Evaluation of combined aquaculture and mangrove replanting in a degraded mangrove site	Aquaculture ponds become self-purifying after mangrove replanting through mangrove nutrient uptake. Fisheries harvests 10% higher with replanted mangroves. Mangrove litterfall contributes up to 26% of cultured fish diet	South China
(Primavera, 1995)	Analysing effects of brackish water pond culture on mangroves	Loss of mangroves is most important consequence of brackish water pond culture, leading to pollution of coastal waters and domestic food crop decline	Philippines
(Shahraki et al., 2014)	Comparison of fish food webs in mangrove and non-mangrove habitats	Plankton and microphytobenthos generally sustain fisheries, regardless of habitat. Presence of mangroves was of minor importance	Persian Gulf
(Sheridan and Hays, 2003)	Assessment of mangrove role as nursery habitats via comparison of nekton quantities across alternate habitats	Direct consumption of mangrove detritus by nekton is minimal; prey abundance may be higher within mangroves. Roots and debris provide refuge from predation, promoting survival	Various
(Walton et al., 2006)	Assessment of direct benefits of a community-based mangrove restoration project	Over 90% of fishers identified mangroves as crucial fish nursery sites. Higher appreciation of benefits and 'willingness to pay' for protection by mangroves fishers	Philippines
(Rahman et al., 2018)	Economic valuation of the most important services from mangroves as perceived by ecosystem dependants	Fisheries provision had the highest value in terms of contributions to wellbeing, followed by honey provision and fodder for livestock, all contributors to human nutrition	Bangladesh

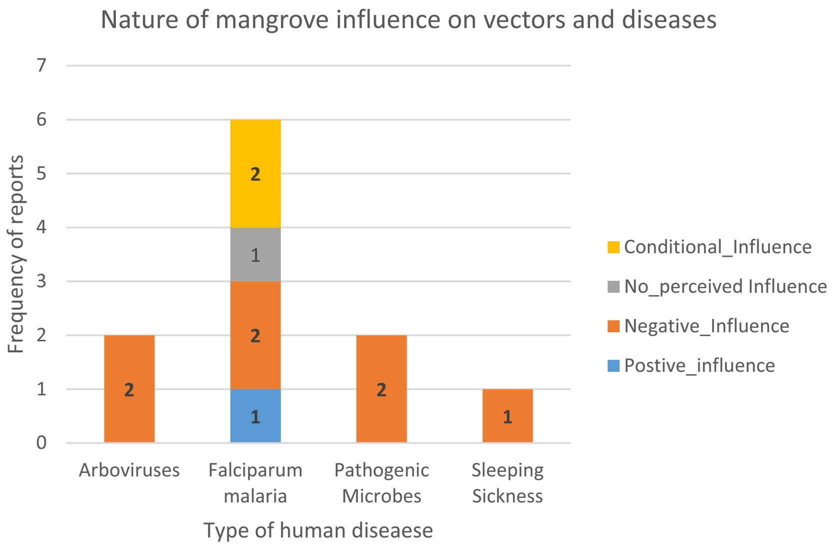

Fig. 7. Nature of reported mangrove influence on disease and disease transmission agents (negative influence implies aggravation of disease risk).

Table 6
Mangrove ecosystem influences on vectors/agents of human disease contained in the review collection.

Disease/vector	Authors	Location	Focus of analysis	Key health findings
Falciparum Malaria/Various Mosquito Nuisance Impacts	(Carney, 2017)	Senegambia, West Africa, Brazilian coast	Overview of mangrove ecosystem use and significance in place-making as part of African and diasporan historical geography	The role of mangroves discussed within the context of sickle-cell-carrying trait in mangrove-dwelling Africans, which confers resistance to falciparum malaria risk posed by mangroves
	(Friess, 2016)	Various historical colonial locations	Quantification of historically discussed mangrove ecosystem services and disservices (1823–1883)	60% of commentary was on disservices, with mangroves especially considered to be disease reservoirs. Contemporary perceptions may have been moulded by such longstanding viewpoints
	(Claflin and Webb, 2017)	Parramatta River, Australia	Impact of land use within 500 m of mangroves, on adult mosquito populations within the mangrove ecosystem	Urbanization degrades wetlands, enhances conditions for pest mosquitoes. Wetland rehabilitation could alleviate public health risks. Short-term, poorly planned interventions could increase mosquito populations and erode public good will
	(Dale et al., 2013)	Australia	Impact of saltmarsh encroachment on saltwater mosquito habitats, and mangrove displacement or replacement of these habitats	Mosquito larval habitats are complex, underpinned by topography and tidal interactions. Not all parts of mangrove ecosystem are suitable habitats. Greater impounding effect of mangroves would restrict oviposition and hatching while increasing fish predation
	(Jacups et al., 2012)	Darwin, Australia	Impact of drainage interventions on mosquito ecology and vegetation; and saltmarshes	Mosquito abundance declines in dry season; some species increase in the wet season. Non-target species disturbance is likely, but results indicate a near return to original drainage conditions
	(Ismail et al., 2018)	Malaysia	Day biting habits of mangrove mosquitoes in Kedah mangrove forests	Biting peaks during dawn and dusk for less disturbed areas but remained irregular throughout the day for others
Sleeping Sickness	(Courtin et al., 2010)	Forecariah, Guinea	Sleeping sickness transmission dynamics in mangrove areas to optimize control	Positive cases were associated with broader walking distances and occupation sites located within or close to mangroves.
Arboviruses	(Hoyos-Lopez et al., 2016)	Colombia	Effects of mangrove fragmentation, expansion of agricultural land use change etc. on emerging and re-emerging arboviruses in coastal areas	Pathogenetic mosquito-borne arboviruses such as West Nile, Dengue, Yellow-fever etc. indicates circulation patterns and possible human health risks in this zone. More data required to investigate vector competence and behaviour
	(Guzman-Teran et al., 2020)	Venezuela	Review of Alphavirus equine encephalitis virus	Strains of the virus continuously circulated in mangroves of Americas by mosquitoes and wild rodents, posing public health risk to nearby human settlements
Pathogenic Microbes	(Ghaderpour et al., 2014)	Malaysia	Faecal bacteria contamination in aquaculture and human settlement impacted mangrove estuary	Various types of bacteria pathogens, including coliforms, present with attendant human health risk
	(Gonzalez et al., 2011)	Venezuela	Microbiological quality of mangrove bivalves used as food	High food-borne illness risk from pathogens including *Clostridium* spp. and *E. coli* detected

who Carney suggests, have in the past used mangroves regions as refuge from foreigners who were less tolerant of the plasmodium malaria risks posed by the ecosystem.

Ten out of 11 articles allude to ecosystem disservices from mangroves in respect of vectors and agents of disease, with one study, (Jacups *et al.*) failing to draw any clear perceivable relationship (See Fig. 7 for breakdown). For papers that reported a conditional influence, anthropogenic influences within the mangrove ecosystem were implicated. Ismail *et al.* emphasise how reduced mangrove disturbance leads to more predictable mosquito biting behaviour, thus presenting better opportunities for vector avoidance. It was however unclear how prevalence of diseases transmitted are affected by modulated vector biting behaviour. Carney further points to the genetic human sickle cell-trait as the condition that confers an advantage upon mangrove dwellers against mosquito-transmitted malaria. The lack of this trait leaves humans susceptible to the malaria threat that exists within tropical mangrove ecosystems.

Three studies (Jacups *et al.*, Ismail *et al.*, Claflin and Webb,) that assessed the impacts of anthropogenic encroachment, shed light on how urban activities degrade wetlands and create the perfect environment for insect pests to proliferate. This, however, does not seem to hold true for all parts of mangrove ecosystems. As revealed by Dale *et al.*, the impounding effects of mangroves could expose mosquito larvae and eggs, for example, to greater predation, while simultaneously restricting oviposition, thereby controlling vector prevalence. Mosquitoes are the commonest vectors for some of the arboviruses for which mangroves serve as reservoirs. Bakau, haemorrhagic fever, dengue, ketapang among others, are spread by mangrove-dwelling mosquito species [67]. Hoyos-Lopez *et al.* provided the sole update on the presence of arboviruses in coastal ecosystems in Colombia, including mangroves. Although vector behaviour and competence, with respect to the appraised mosquito-borne viruses (including yellow, dengue and West Nile fever), were not specifically investigated, the authors unveiled circulation patterns within mangroves that translate into possible human health risks.

Courtin *et al.* was the sole study that focused on trypanosomiasis (sleeping sickness), concluding that human occupational activity close to mangroves increases transmission risk, due to the habitat support services mangroves provide for the tsetse fly vectors. Generally, the closer the mangrove frontier is to human activity, the higher the health risk from exposure to vector organisms (Table 6). In reducing this risk, drainage interventions have proven to be helpful in some instances, as reported by Jacups *et al.* Claflin and Webb further opine that following such interventions, circumstances may return to the pre-drainage conditions with time, provided the original intervention is properly planned and executed in a minimally ecologically disruptive manner. Otherwise, public health risks rise with human interference in mangrove ecosystems, leading to the erosion of public good will towards the wetland in respect of proliferation of nuisance insects and diseases.

3.5. Summary

The medicinal value of mangroves resides in the bioactive metabolite richness of mangrove plants, endophytic fungi and associated actinobacteria. Aqueous and organic extracts of leaves, barks, stems, and roots of mangrove plants exhibit varying bioactive properties, which manifest in inhibitory action against pathogenic and food spoilage bacteria and fungi. Additional medicinal worth lies in the anti-inflammatory, antidiabetic, anticancer, antioxidant and antipyretic properties of extracts, which were reported in that decreasing order of abundance in the review literature. The most widely reported property is antibacterial activity.

Regulation of sediment and aquatic chemistry is a function of mangrove ecosystems that delivers pollution control services to human communities. The evidence contained in this review points to the fact that heavy and trace metal remediation, as well as attenuation of organic PCB and PAH pollutants, occurs in the mangrove environment. This function is demonstrated, in most instances, by the safe levels of toxic contaminants reported for mangrove ecosystem water and sediments despite pollution.

The mediated bioaccumulation of otherwise harmful mineral and organic pollutants, through ecological interventions in the mangrove ecosystem, appears to deliver safe pollutant levels in mangrove goods such as fish and crustaceans. The risk of metal remobilization following abscission events, however, lingers.

The widely held belief that mangroves are vital for the provision of goods of human nutritional value seems to hold true for the substance of this review. Protective habitat support, reinforced by carbon and therefore organic matter richness characteristics, enables mangrove ecosystems to sustain breeding of edible vertebrate and invertebrate fauna in a manner that fortifies and diversifies human food chains. Studies regarding detritus and nutrient support for fisheries food chains, as well as nursery and shelter provision for juveniles, make up 82% of relevant papers. To a lesser extent, other nutritional benefits come in the form of honey production from mangrove-foraging honeybees, and provisioning services for grazing food chains. The acknowledgement of nutritional benefits of mangrove goods is sufficient to influence livelihood and wellbeing choices of low-income mangrove dwellers. One shortfall in the literature considered, however, was the fact that there weren't as many studies about Africa as there were about other tropical regions. Only one East African study (Kenya) was called up, highlighting a blind portion in the literature in terms of how the mangroves of other parts, such as West Africa, influence food supply and nutrition in surrounding settlements.

Regarding threats posed to human health by a variety of harmful microbial constituents of waste discharges, there is little indication of competent mangrove mediation. Intervention is extended, in rare instances, to scenarios of infectious disease transmission, when ecological integrity facilitates natural vector and pathogen control mechanisms. However, the strength of the evidence of this nature is minimal in the current review. Because mangrove provide suitable habitats for most food-borne pathogens, food goods from microbe-contaminated mangrove settings were largely shown to pose risks to human health. The aquatic mangrove environment, which maintains the life cycles of some nuisance insects and vectors, leads to abundance of vectors organisms, and a resultant prevalence of vector-borne diseases in mangrove populations.

Only English language publications from the ISI 'Web of Science Database' have been included in this review, and the vast variety of measurement parameters in the records captured make a robust, comparative meta-analysis of findings unfeasible. Nonetheless, considering the health aspects of human wellbeing together, the evidence indicate that mangroves exert a more desirable than deleterious effect. For some of these links to human health, a greater consensus exists in the literature, whereas other evidence requires further targeted investigations.

4. Conclusions

Mangroves are useful to human society by virtue of their ecosystem diversity, which translates into the supply of a variety of beneficial goods and services. Some of these services, such as provision of medicines, pollution regulation and provisioning for food goods are generally health promoting. Given the global antibiotic resistance conundrum currently confronting the pharmaceutical industry, the outstanding antibiotic bioactivity of mangrove extracts is particularly promising. Conditions of contaminant load, ecological integrity, nature of anthropogenic alteration as well as magnitude of consumption of affected food products, exert limiting effects on mangrove bioremediation benefits. Studies reflect a focus on mangrove ecosystem impacts on food production (e.g. quantity of fisheries) with little to nothing reported in relation to nutritional quality (e.g., unique vitamin and mineral content of mangrove-supported food products). Bridging this gap in knowledge could reveal how mangrove influence on availability of diversified food options helps humans meet specific nutritional needs.

Conversely, some disservices to humanity emanate from otherwise positive habitat support functions of mangrove ecosystems. Notable among these are the risks associated with pathogenic microbe transmission through human food chains. Further risks lie with parasitic and other disease agents like arboviruses through mangrove-dwelling vectors. In the absence of biological or anthropogenic interventive mechanisms to counteract this cocktail of disease entrenching effects, the combined outcomes lend credence to the infamous reputation of mangroves as far as human disease risk is concerned. Not enough information appears to be available to explain the potentially conditional relationships between mangrove ecosystem processes and human disease outcomes. Especially, more investigations are required to clarify some of the theorised mix of consequences outlined in works like Duke *et al.* [18], and how they are influenced by changing states of ecosystems and social ecology.

Exploiting mangrove ecosystems for health-supporting benefits could obstruct functioning cycles that and affect the ability of the ecosystems to supply other services. Further insights into how to limit anthropogenic ecosystem stresses, could facilitate management strategies that enable these ecosystems to continue supplying crucial health-promoting ecosystem services, particularly in marginal communities.

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Appendix A. Supplementary data

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