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ANTHROPOGENIC UNDERWATER SOUND AND ITS EFFECTS ON FISHES: A REVIEW OF SOURCES, SENSORY MECHANISMS, BIOLOGICAL RESPONSES, ECOLOGICAL CONSEQUENCES, AND RESEARCH PRIORITIES

Lakhnarayan Kumar Bhagarathi [1, 2, *], Aarif Baksh [2], Phillip N. B. Da Silva [1, 2], Vandevi Bhikam [1], Sushmita Kalika-Singh [2], Yunita Arjune [2] and Ferial Pestano [2]

[1] Institute for Marine and Riverine Ecologies and Economies, University of Guyana, Berbice Campus, John's Science Centre, Corentyne, Berbice, Guyana, South America.
[2] Faculty of Natural Sciences, University of Guyana, Berbice Campus, Tain, Corentyne, Berbice, Guyana, South America.
* Corresponding Author

ORCID Details
Lakhnarayan Kumar Bhagarathi: https://orcid.org/0000-0001-7241-3830

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ABSTRACT

Anthropogenic sound has become an increasingly important environmental stressor in marine, estuarine, and freshwater ecosystems. Fishes rely on acoustic information for communication, orientation, habitat selection, predator and prey detection, social interactions, and reproduction. Consequently, anthropogenic sound may interfere with biologically important sensory processes and produce behavioural, physiological, auditory, developmental, reproductive, and ecological effects. This review synthesizes literature on the major sources of anthropogenic sound affecting fishes and evaluates the mechanisms through which sound exposure produces biological responses. Evidence indicates that the effects of sound are strongly influenced by its frequency, intensity, duration, temporal pattern, repetition rate, propagation characteristics, and the distance between the source and receiver. Fish responses are also species-specific and depend on auditory sensitivity, anatomical adaptations, life stage, behavioural state, habitat, and environmental context. Documented effects include behavioural avoidance, altered swimming and feeding, acoustic masking, temporary hearing threshold shifts, stress responses, changes in energy allocation, reproductive disruption, and effects on early-life development. Impulsive sources, including pile driving and seismic airguns, may pose acute risks under certain exposure conditions, whereas continuous vessel and shipping noise can create chronic masking and disturbance over large spatial areas. However, important uncertainties remain because relatively few fish species have been investigated, particle motion is often inadequately measured, laboratory exposure conditions may differ from natural sound fields, and direct evidence linking individual responses to population-level consequences remains limited. The review concludes that anthropogenic sound should be regarded as a biologically relevant form of aquatic pollution. Future research should prioritize species-specific exposure assessment, long-term field studies, measurement of both sound pressure and particle motion, investigation of cumulative stressors, and greater representation of tropical, estuarine, freshwater, and developing-world ecosystems.

Keywords: Anthropogenic Sound; Underwater Noise; Fishes; Fish Bioacoustics; Acoustic Pollution; Behaviour; Stress; Masking; Reproduction; Fisheries

1 INTRODUCTION

Sound is a component of aquatic environments. Unlike light, which may be rapidly attenuated in turbid or deep water, sound can travel considerable distances and provides fishes with important information about their surroundings. Fishes use acoustic and vibrational cues in communication, orientation, habitat selection, predator detection, prey detection, social interactions, and reproductive behaviour [14, 22].

Natural aquatic soundscapes contain sounds generated by wind, waves, rainfall, flowing water, geological processes, aquatic organisms, and other environmental phenomena. However, human activities increasingly contribute additional sound to these environments. Shipping, motorized vessels, seismic exploration, pile driving, coastal construction, dredging, sonar, and offshore industrial activities may also alter both the intensity and composition of ambient sound [13, 25].

The biological effects of anthropogenic sound cannot be understood simply by determining whether a fish responds to a sound. A response may depend on the acoustic properties of the source, the received exposure, the sensory capabilities of the fish, and the ecological circumstances under which exposure occurs. For example, a brief avoidance response may have little long-term consequence in one habitat but may become ecologically significant if repeated disturbance prevents feeding, disrupts spawning, or displaces fish from essential nursery habitat.

A meta-analysis by Cox *et al.* (2018) [6] demonstrated that anthropogenic noise can affect fish behaviour and physiology. Similarly, Popper and Hawkins (2019) [22] emphasized that anthropogenic sound may affect fishes through hearing impairment, masking, behavioural disturbance, and physiological stress. More recently, reviews of field studies have highlighted the importance of improving ecological realism and determining whether short-term experimental responses translate into consequences for wild populations [19].

Basdeo *et al.* (2025) [3] provide a particularly relevant synthesis for understanding the effects of anthropogenic sound on fishes, identifying underwater noise from offshore seismic surveys, shipping, sonar systems, and oil and gas activities as an increasingly pervasive disturbance to marine soundscapes. The review emphasizes that fishes are especially vulnerable because they depend on acoustic cues and vibrations for essential ecological functions, including communication, foraging, mating, navigation, and habitat use. Anthropogenic sound can therefore disrupt these functions through acoustic masking and behavioural disturbance, while more intense or prolonged exposure may contribute to hearing impairment, tissue damage, endocrine disruption, elevated stress responses, and developmental abnormalities in early life stages. Importantly, the authors highlight considerable species-specific variation in sensitivity, indicating that the consequences of noise exposure depend on the acoustic characteristics of the source and the biological and sensory characteristics of the exposed fish. This evidence is particularly relevant to fisheries and marine conservation because disturbances to feeding, reproduction, growth, sensory development, and survival may ultimately influence fish recruitment and population sustainability. Basdeo *et al.* (2025) [3] further emphasize the urgency of context-specific research, particularly given the expansion of offshore industrial activities, where increased seismic exploration, shipping, and oil and gas development may alter marine acoustic environments and potentially affect local fish biodiversity.

This review examines the principal sources of anthropogenic sound, fish auditory systems, mechanisms of acoustic impact, and documented biological responses. Particular attention is given to species-level evidence and the taxonomic diversity of fishes investigated.

2 MATERIAL AND METHODS

2.1 Search Strategy

A systematic thematic literature review was conducted to synthesize available information on the impacts of anthropogenic sound on fishes. The review prioritized recent peer-reviewed studies published between 2020 and 2025 to provide contemporary scientific evidence while also incorporating influential earlier studies that established fundamental knowledge of fish hearing, underwater acoustics, sound exposure, and biological responses.

Searches were conceptually guided by the terms “anthropogenic sound,” “underwater noise,” “fish,” “fish hearing,” “fish bioacoustics,” “shipping noise,” “boat noise,” “seismic airgun,” “pile driving,” “construction noise,” “sound exposure,” “acoustic masking,” “temporary threshold shift,” “stress,” “cortisol,” “fish reproduction,” “larval fish,” “fish development,” “fish behaviour,” and “particle motion.”

The literature was examined thematically according to:

- Sources and characteristics of anthropogenic sound.
- Fish hearing and auditory sensitivity.
- Behavioural responses.
- Acoustic masking and communication.
- Physiological and stress responses.
- Hearing impairment and physical injury.
- Reproductive effects.
- Developmental and early-life-stage effects.
- Ecological and population-level implications.
- Knowledge gaps and management strategies.

The organization and systematic thematic approach of this review follow the general structure of review articles, including separate sections for search strategy, inclusion criteria, literature results, thematic discussion, knowledge gaps, and conclusions.

2.2 Inclusion Criteria

Publications were considered relevant if they met one or more of the following criteria:

- Peer-reviewed studies or authoritative scientific reviews addressing anthropogenic sound exposure in fishes.
- Research examining behavioural, auditory, physiological, molecular, developmental, reproductive, or ecological responses.
- Studies identifying fish species and, where possible, their taxonomic order and family.
- Recent studies published primarily between 2020 and 2025.
- Earlier foundational studies necessary for understanding the development of fish bioacoustics and underwater-noise research.
- Laboratory, experimental, mesocosm, and field studies with sufficiently described sound exposures.
- Publications written in English.

2.3 Evidence Synthesis

The selected literature was grouped according to the type of anthropogenic sound and the biological level at which effects were reported. Evidence was interpreted cautiously because an observed physiological or behavioural response does not necessarily demonstrate a population-level effect. Consequently, this review distinguishes between directly observed effects, mechanistically supported consequences, and broader ecological inferences.

3 RESULTS

Literature for this review was accessed using various academic search engines, bibliographic databases, publisher platforms, and open-access repositories, including Google Scholar, ResearchGate, Academia, Semantic Scholar, R Discovery, OiPub, ScienceDirect, PubMed/MEDLINE, SpringerLink, Web of Science, Scopus, Wiley Online Library, SciSpace, and institutional repositories. Reference lists of relevant review articles, experimental studies, and primary research papers were also examined to identify additional literature relating specifically to anthropogenic sound, underwater noise, fish bioacoustics, hearing, behaviour, physiology, reproduction, and ecological responses. The majority of journal articles were accessible through open-access platforms, publisher websites, institutional access, or other academic repositories. Where publications were identified through their Digital Object Identifiers (DOIs), the DOI was used to locate the original publication or an accessible version of the article.

An extensive and comprehensive collection of published literature was accumulated when the selected search terms were utilised. The searches focused on literature relating to the sources and characteristics of anthropogenic sound, fish auditory biology, acoustic exposure, behavioural responses, physiological stress, hearing impairment, communication, reproduction, development, and potential ecological consequences. The principal search categories used were as follows:

- **Anthropogenic sound affecting fishes:** Literature examining the general effects of human-generated underwater sound on fish species, populations, and aquatic communities.
- **Underwater noise and fish behaviour:** Studies investigating changes in swimming, avoidance, escape responses, habitat use, movement patterns, feeding behaviour, foraging efficiency, vigilance, and predator–prey interactions following sound exposure.

- **Fish hearing and bioacoustics:** Research examining fish auditory systems, hearing sensitivity, sound-pressure detection, particle-motion detection, auditory specialisations, and differences in acoustic sensitivity among fish taxa.
- **Shipping and vessel noise:** Studies examining the effects of commercial shipping, recreational boats, fishing vessels, and other vessel activities on fish behaviour, communication, habitat use, stress, and feeding.
- **Seismic surveys and fishes:** Research investigating the effects of seismic airguns and other geophysical exploration activities on fish hearing, behaviour, distribution, physiology, and potential injury.
- **Pile driving and construction noise:** Studies examining impulsive and construction-related sound generated by pile driving, offshore construction, coastal development, and associated industrial activities.
- **Acoustic masking in fishes:** Literature investigating how anthropogenic sound interferes with the detection, discrimination, and interpretation of biologically important acoustic signals associated with communication, predator detection, prey detection, orientation, and reproduction.
- **Physiological and stress responses:** Studies examining cortisol and other stress-related responses, metabolic changes, oxidative stress, energy expenditure, molecular responses, and other physiological consequences of sound exposure.
- **Auditory impairment and injury:** Research investigating temporary threshold shifts, changes in hearing sensitivity, permanent auditory effects, barotrauma, and possible damage to auditory structures and tissues.
- **Anthropogenic sound and fish reproduction:** Studies examining the effects of sound on courtship, mating behaviour, acoustic communication, spawning activity, endocrine regulation, gonadal development, reproductive success, parental care, and offspring production.
- **Effects on eggs, larvae, and juvenile fishes:** Research investigating developmental responses, growth, morphology, survival, sensory development, behaviour, energy allocation, and early-life vulnerability to anthropogenic sound.
- **Ecological and population-level consequences:** Studies examining the potential implications of sound-induced behavioural, physiological, auditory, and reproductive effects for habitat use, predator-prey relationships, recruitment, population structure, biodiversity, and ecosystem functioning.
- **Methods used to investigate anthropogenic sound effects:** Literature examining laboratory exposure experiments, field studies, passive acoustic monitoring, hydrophone measurements, particle-motion measurements, auditory testing, behavioural observations, physiological assays, and molecular approaches.
- **Cumulative stressors and anthropogenic sound:** Studies examining interactions between underwater noise and other environmental pressures, including climate change, increasing water temperature, hypoxia, pollution, habitat degradation, fishing pressure, and industrial development.

When using Google Scholar and other academic databases to search for information on anthropogenic sound and its effects on fishes, a substantial number of publications were retrieved across the different search categories. The literature included both recent publications, particularly those published between 2020 and 2025, and earlier foundational studies. Earlier studies were retained if they provided important information on fish hearing, acoustic ecology, seismic exposure, pile-driving effects, auditory impairment, or the biological mechanisms through which sound can affect fishes. The search results were subsequently refined according to publication relevance, subject area, year of publication, sound source, biological response, fish taxonomic focus, study design, and the extent to which individual papers contributed to the central objectives of the review.

The literature eventually selected for the review included publications addressing several major dimensions of the relationship between anthropogenic sound and fishes. These consisted of studies directly examining behavioural responses to vessel noise, seismic airguns, pile driving, and experimentally generated sound, as well as investigations of differences in hearing sensitivity among fish species. Some additional studies were selected because they provided information on the physiological and sensory mechanisms underlying fish responses, including acoustic masking, stress activation, altered energy allocation, temporary hearing threshold shifts, and possible injury to auditory structures [21, 22].

The studies that were reviewed demonstrated substantial taxonomic variation in the evidence base. Research has included representatives from several fish Orders and Families, including Esociformes (*Esox lucius*, Esocidae), Cypriniformes (*Couesius plumbeus*, Leuciscidae; *Danio rerio*, Danionidae), Salmoniformes (*Coregonus nasus* and *Oncorhynchus tshawytscha*, Salmonidae), Gadiformes (*Gadus morhua*, Gadidae), Gobiiformes (*Pomatoschistus microps*, Gobiidae), Batrachoidiformes (*Halobatrachus didactylus*, Batrachoididae), Acipenseriformes (*Acipenser fulvescens*, Acipenseridae), Cichliformes (*Oreochromis mossambicus*, Cichlidae), and sciaenid fishes, including *Sciaenops ocellatus* and *Argyrosomus regius*. However, the number of species investigated remains small relative to global fish diversity. This is an important limitation because fishes differ considerably in auditory anatomy, hearing sensitivity, reliance on acoustic information, life-history characteristics, habitat use, and ability to avoid acoustic disturbance.

Not all papers retrieved for this research focused directly on experimentally exposing fishes to anthropogenic sound. Some studies focused primarily on fish bioacoustics and hearing mechanisms, while others examined underwater soundscapes and the major human activities contributing to elevated sound levels. Several publications investigated behavioural responses such as avoidance, altered swimming, reduced feeding, habitat displacement, or changes in predator–prey interactions. Other studies examined the effects of noise on stress physiology, energy allocation, oxidative stress, endocrine activity, or molecular pathways. These publications were considered relevant because they provided mechanistic information for understanding how acoustic disturbance could affect fish performance and fitness.

A considerable proportion of the literature focused on specific sound sources. Studies of commercial shipping and vessel noise investigated the consequences of chronic or repeated exposure to anthropogenic sound, particularly acoustic masking and behavioural disturbance. Seismic-airgun studies provided important evidence concerning the potential effects of repeated impulsive exposure on fish hearing and behaviour. For example, studies involving northern pike (*Esox lucius*), broad whitefish (*Coregonus nasus*), and lake chub (*Couesius plumbeus*) demonstrated that responses to seismic sound can differ among species, with temporary threshold shifts reported in some species but not in others under the conditions investigated [23]. This variation demonstrated that fish responses cannot be accurately predicted using a single universal exposure threshold.

Similarly, research involving pile driving and other intense impulsive sounds provided evidence concerning injury thresholds, physiological disturbance, and effects on auditory structures. Studies involving Chinook salmon (*Oncorhynchus tshawytscha*) and other fish species demonstrated that exposure characteristics, anatomy, and species-specific sensitivity are important determinants of risk [5, 11]. These studies were particularly relevant because pile driving and coastal construction represent increasingly common anthropogenic activities in coastal and offshore environments.

Some publications focused specifically on the effects of anthropogenic sound on fish communication and acoustic masking. These studies examined how elevated background noise can interfere with the ability of fishes to detect biologically important sounds. Such interference may affect the detection of mating and courtship signals, territorial communication, predator cues, prey-generated sounds, and orientation cues. The literature indicated that masking may be ecologically important even when sound exposure is insufficient to cause direct physical injury because persistent background noise can alter information transfer and sensory functioning over broad spatial areas [22, 25].

The results also identified an important body of literature relating to reproduction and early-life development. Some studies examined breeding behaviour, courtship, reproductive communication, and spawning, while others investigated endocrine responses and potential disruption of reproductive pathways. Research involving the Lusitanian toadfish (*Halobatrachus didactylus*) demonstrated that vessel-related noise can affect breeding behaviour and reproductive outcomes [1]. More recent studies involving zebrafish (*Danio rerio*) have further investigated relationships between repeated underwater noise exposure, reproductive behaviour, and endocrine processes. These findings were important because reproductive disruption may have consequences that extend beyond immediate exposure and potentially influence recruitment.

Studies on eggs, larvae, and juvenile fishes were also included because early-life stages may have limited capacity to avoid unfavourable acoustic environments. Research involving larval Atlantic cod (*Gadus morhua*) examined the effects of noise exposure on behaviour, growth, and development [17]. Similarly, research on the common goby (*Pomatoschistus microps*) indicated that chronic anthropogenic noise may influence offspring development and condition [4]. Such findings suggest that anthropogenic sound may affect fishes during sensitive developmental periods when changes in growth, energy allocation, sensory development, or body condition could potentially influence later survival and performance.

Some publications focused primarily on physiological and molecular responses rather than on immediately observable behaviour. These studies investigated stress-related pathways, metabolic effects, oxidative stress, and other physiological mechanisms through which chronic or repeated sound exposure could influence fish health and performance. Such studies were relevant because behavioural responses alone may underestimate the biological effects of anthropogenic sound. A fish may not visibly avoid a sound source but may nevertheless experience stress, altered energy expenditure, sensory interference, or physiological disturbance.

Figure 1: Pathway of anthropogenic sound impacts on fish and ecological consequences

The literature also included several broad reviews and meta-analyses examining the overall state of knowledge concerning aquatic noise. These studies were important in identifying general patterns and major limitations within the evidence base. For example, Cox *et al.* (2018) [6] reported broad effects of aquatic noise on fish behaviour and physiology, while Pieniazek *et al.* (2023) [19] highlighted the importance of field studies and the challenges associated with interpreting noise effects in wild fish populations. Basdeo *et al.* (2025) [3] further emphasized the increasing importance of bioacoustic disruption in marine environments, particularly as shipping, seismic exploration, offshore industrial activities, and other human activities continue to modify natural soundscapes.

The results further demonstrated that anthropogenic sound may affect fishes through multiple interconnected pathways rather than through a single biological mechanism. The general pathway identified from the literature can be summarised as seen in Figure 1.

However, the literature consistently indicates that the strength of these pathways is influenced by several moderating factors. These include fish species, taxonomic rank, hearing ability, life stage, frequency sensitivity, exposure intensity, duration, repetition, distance from the source, habitat characteristics, ambient sound levels, and whether exposure occurs during biologically sensitive activities such as feeding, migration, courtship, spawning, or early development.

A major observation when conducting the literature search was that research on anthropogenic sound affecting fishes is not evenly distributed among geographical regions, ecosystems, sound sources, or fish taxa. Considerable information is available for selected temperate marine environments, commercially important species, and experimentally accessible freshwater fishes. However, comparatively less information is available for many tropical, estuarine, riverine, and developing-world ecosystems. There is particularly limited information concerning the responses of many Neotropical fish species.

This geographical limitation is highly relevant to Guyana and the wider Neotropical region. Guyana possesses extensive riverine, estuarine, coastal, and marine ecosystems supporting diverse freshwater and marine fish assemblages. At the same time, increasing shipping, maritime transportation, offshore industrial activity, seismic exploration, coastal development, and other human activities have the potential to alter regional aquatic soundscapes. However, much of the current understanding of fish responses is derived from non-Neotropical species. Consequently, caution is required when directly applying findings from Atlantic cod, salmonids, pike, gobies, or zebrafish to native Guyanese fish species.

However, important knowledge gaps remain regarding the effects of chronic exposure, cumulative acoustic disturbance, particle motion, species-specific hearing sensitivity, early-life development, reproduction, long-term survival, recruitment, and population-level consequences. There is also a need for more field-based *in situ* studies because controlled laboratory experiments, although scientifically valuable, may not fully reproduce the complex sound fields and ecological conditions experienced by wild fishes.

Therefore, although a substantial body of literature was identified, the final studies used in this review were selected based on their relevance to the central objective of understanding how anthropogenic sound affects fishes, which sound sources pose potential risks, which behavioural and physiological mechanisms are involved, how responses differ among fish species and life stages, and what ecological consequences may result from prolonged or repeated exposure.

4 DISCUSSION

4.1 Major Sources of Anthropogenic Sound Affecting Fishes

The literature indicates that research on anthropogenic sound has expanded substantially, although evidence remains unevenly distributed among sound sources, ecosystems, and fish taxa. Shipping and vessel noise have received considerable attention because of their widespread and persistent nature. Seismic exploration and pile driving have also been extensively studied because they can generate intense impulsive sounds.

Anthropogenic sound sources differ in their spectral content, amplitude, temporal pattern, and spatial footprint. Continuous or quasi-continuous sources such as shipping may elevate background sound over broad areas, whereas impulsive sources such as pile driving and seismic air guns can produce high-amplitude events with rapid onset. These differences are ecologically important because masking is particularly associated with elevated background noise, while acute injury and temporary threshold shifts are more closely associated with sufficiently intense exposures and cumulative received energy [22].

Shipping is among the most important contributors to persistent anthropogenic sound in the world's oceans (Table 1). Its importance arises not only from source intensity but also from the widespread nature of vessel traffic. Chronic low-frequency noise may overlap with frequencies relevant to some fish species, potentially reducing the ability to detect environmental or biological signals.

Pile driving and seismic exploration differ because they produce intense impulsive signals. These activities may generate strong acoustic exposure close to the source, particularly when repeated over extended periods. The potential for biological effects therefore depends substantially on distance, propagation conditions, exposure duration, and the biological characteristics of the exposed fish.

Table 1: Major anthropogenic sound sources, their characteristics, potential impacts on fishes, and representative literature

Sound source	Principal acoustic characteristics	Major exposure concern	Potential effects on fishes	Representative authors
Commercial shipping	Predominantly continuous, often low-frequency	Chronic exposure over large spatial areas	Masking, altered behaviour, stress, habitat displacement	Hildebrand (2009) [13]; Slabbekoorn *et al*., (2010) [25]; Popper & Hawkins (2019) [22]
Recreational vessels	Intermittent to chronic; variable frequencies	Frequent disturbance in coastal and freshwater habitats	Reduced feeding, altered swimming, stress, communication interference	Slabbekoorn *et al.* (2010) [25]; Simpson *et al*., (2016) [24]; de Jong *et al.* (2020) [7]
Seismic airguns	Repeated high-energy impulsive signals	Acute and repeated exposure	Startle, avoidance and temporary hearing threshold shifts in some species	McCauley *et al*., (2000) [16]; Popper *et al.* (2005) [23]; Popper & Hastings (2009) [21]
Pile driving	High-intensity impulsive broadband sound	High local exposure during construction	Injury, barotrauma, auditory effects and behavioural disturbance	Halvorsen *et al.* (2012) [11]; Popper & Hastings (2009) [21]; Casper *et al.* (2013) [5]
Dredging and coastal construction	Continuous and intermittent broadband noise	Prolonged localized disturbance	Masking and behavioural displacement	Slabbekoorn *et al*., (2010) [25]; Tougaard *et al*., (2015) [26]; Popper & Hawkins (2019) [22]
Sonar and industrial activity	Variable tonal and broadband signals	Frequency- and species-dependent exposure	Behavioural and physiological disturbance	Popper & Hastings (2009) [21]; Popper & Hawkins (2019) [22]

4.2 How Fishes Perceive Sound

Fish hearing is highly diverse (Table 2). All fishes possess inner ears containing otolithic organs that respond to acceleration and particle motion. In some species, especially those with anatomical specialisations that couple gas-filled structures to the inner ear, sound pressure sensitivity is enhanced and hearing extends to higher frequencies [20, 22]. Other taxa are principally sensitive to lower-frequency particle motion. Consequently, broad taxonomic generalisations about susceptibility are inappropriate without considering auditory anatomy and the relevant component of the acoustic field [20, 22].

A major methodological issue is that underwater sound contains both pressure and particle-motion components. Many studies report sound pressure alone, even though particle motion may be the more biologically relevant cue for species lacking strong pressure sensitivity. The failure to measure both components can therefore reduce ecological interpretability and complicate comparison among experiments.

Table 2: General hearing characteristics of different fish species

Species (common name)	Scientific name	Order	Family	General hearing characteristic	Representative source
Atlantic cod	*Gadus morhua*	Gadiformes	Gadidae	Low-frequency specialist; responds to biologically relevant low-frequency sound	McCauley *et al*., (2003) [15]
Rainbow trout	*Oncorhynchus mykiss*	Salmoniformes	Salmonidae	Moderate hearing range; particle-motion sensitivity important	Wysocki *et al*., (2006) [28]
Zebrafish	*Danio rerio*	Cypriniformes	Cyprinidae	Broad auditory sensitivity relative to many teleosts	Neo *et al.* (2014) [18]; Amorim *et al*., (2017) [2]
Nile tilapia	*Oreochromis niloticus*	Cichliformes	Cichlidae	Detects low-frequency and communication-related stimuli	Fay & Popper, (2000) [10]
Giant grouper	*Epinephelus lanceolatus*	Perciformes	Serranidae	Low-frequency hearing; vulnerable to intense impulsive exposure	Simpson *et al.* (2015) [24]
European sea bass	*Dicentrarchus labrax*	Moroniformes	Moronidae	Hearing and behavioural responses influenced by environmental noise	Amorim *et al*., (2017) [2]
Lake whitefish	*Coregonus clupeaformis*	Salmoniformes	Coregonidae	Low-frequency sensitivity; spawning behaviour may be noise-sensitive	Popper *et al*., (2023)
Larval herring	*Clupea harengus*	Clupeiformes	Clupeidae	Early life stages may show strong responses to impulsive noise	Neo *et al*., (2014) [18]

4.3 Fish Hearing and Differential Susceptibility

Understanding the impacts of anthropogenic sound requires an understanding of how fishes detect sound. All fishes are capable of detecting particle motion. Many species also detect sound pressure through the inner ear. Some taxa possess auditory specializations involving the swim bladder or other structures that enhance sensitivity to particular components or frequencies of sound [14, 22].

Fish hearing is diverse and therefore it is scientifically inappropriate to assume that a sound producing a particular response in one species will have the same effect in another. Table 3 presents fish species, their exposure and response to anthropogenic sound that were documented in previous studies.

Table 3: Representative fish species investigated in relation to anthropogenic sound

Species	Order	Family	Exposure or context	Reported response	Authors
Esox lucius (Northern pike)	Esociformes	Esocidae	Seismic airgun exposure	Temporary hearing threshold shift with recovery reported	Popper *et al.* (2005) [23]
Coregonus nasus (Broad whitefish)	Salmoniformes	Salmonidae	Seismic airgun exposure	No threshold shift reported under study conditions	Popper *et al.* (2005) [23]
Couesius plumbeus (Lake chub)	Cypriniformes	Leuciscidae	Seismic airgun exposure	Temporary threshold shift reported	Popper *et al.* (2005) [23]
Oncorhynchus tshawytscha (Chinook salmon)	Salmoniformes	Salmonidae	Pile-driving exposure	Injury thresholds investigated	Halvorsen *et al.* (2012) [11]
Acipenser fulvescens (Lake sturgeon)	Acipenseriformes	Acipenseridae	Impulsive sound exposure	Species-specific injury and exposure responses examined	Halvorsen *et al.* (2012) [11]
Oreochromis mossambicus (Mozambique tilapia)	Cichliformes	Cichlidae	Pile-driving exposure	Inner-ear effects investigated	Casper *et al.* (2013) [5]
Gadus morhua (Atlantic cod)	Gadiformes	Gadidae	Larval exposure to noise	Effects on growth and developmental performance	Nedelec *et al.* (2016) [17]
Pomatoschistus microps (Common goby)	Gobiiformes	Gobiidae	Early-life chronic noise exposure	Effects on brood and offspring condition	Blom *et al.* (2024) [4]
Danio rerio (Zebrafish)	Cypriniformes	Danionidae	Reproductive noise exposure	Effects on reproductive and endocrine processes	Zhang *et al.* (2025) [29]
Halobatrachus didactylus (Lusitanian toadfish)	Batrachoidiformes	Batrachoididae	Boat-noise exposure	Effects on breeding behaviour and reproduction	Amorim *et al*. (2022) [1]
Sciaenops ocellatus (Red drum)	Acanthuriformes	Sciaenidae	Larval sound exposure	Behavioural responses to anthropogenic sound treatments	Waddell *et al.* (2023) [27]
Argyrosomus regius (Meagre)	Acanthuriformes	Sciaenidae	Embryonic and larval exposure	Developmental and energetic responses investigated	Amorim *et al*. (2022) [1]; Waddell *et al.* (2023)

Popper *et al.* (2005) [23] found temporary hearing threshold shifts in some species but not in others under the conditions investigated. This illustrates why a universal noise threshold is unlikely to adequately represent all fishes. The contrasting responses of northern pike, lake chub, and broad whitefish to seismic-airgun exposure provide an important example of species-specific susceptibility.

4.4 Conceptual Pathways Linking Anthropogenic Sound to Fish Responses

Anthropogenic sound can affect fishes through a sequence of connected processes as represented in Figure 2.

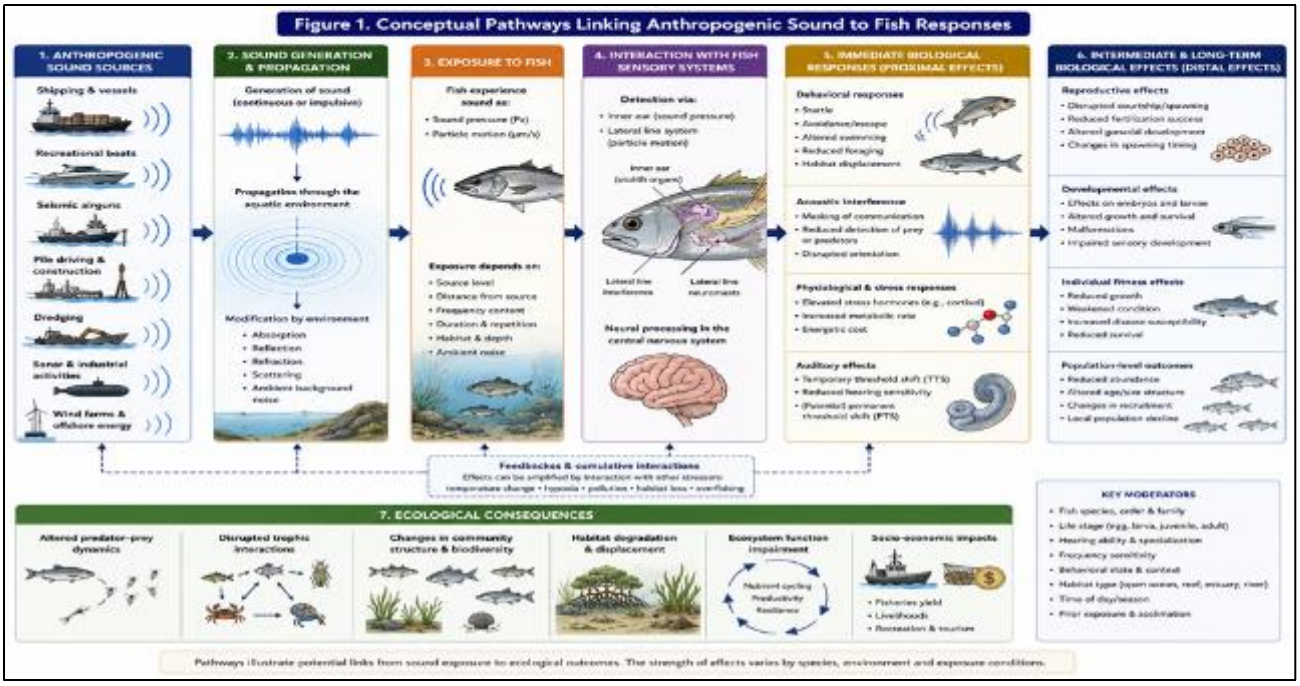

Figure 2: Conceptual pathways of this review

This framework is not strictly linear. Feedbacks occur because behavioural avoidance can reduce exposure, while habitat displacement can create new energetic costs. Likewise, repeated physiological responses may accumulate over time, and multiple sound sources may interact with other stressors such as temperature change, hypoxia, fishing pressure, habitat degradation, and chemical pollution.

The final ecological consequence is not determined by sound exposure alone. It is mediated by numerous factors, including: fish species and family; hearing capability; developmental stage; frequency overlap; sound intensity; exposure duration; repetition rate; distance from the source; habitat characteristics; ambient sound; availability of alternative habitat; presence of predators or prey; and reproductive status.

5 BIOLOGICAL IMPACTS OF ANTHROPOGENIC SOUND ON FISHES

5.1 Behavioural Effects of Anthropogenic Sound

Behavioural responses are among the most frequently documented consequences of anthropogenic sound. Fishes may show avoidance, reduced habitat use, altered swimming, changes in schooling, disrupted feeding, reduced predator detection, modified anti-predator responses, and altered social or reproductive behaviour [24]. Such effects can arise directly when sound is aversive or indirectly when noise masks environmental cues. For example, boat noise can interfere with parental care and communication-related behaviour, while repeated disturbance may displace fishes from otherwise suitable habitats [24].

Cox *et al.* (2018) [6], in their meta-analysis, found evidence that anthropogenic noise can negatively affect several aspects of fish behaviour and physiology. Of particular concern are responses that create energetic costs. For example, repeated avoidance may force fish to abandon productive feeding grounds, while increased vigilance may reduce time available for feeding.

Behavioural change is not necessarily equivalent to ecological harm; however, repeated changes in time allocation can generate energetic and fitness costs. Increased vigilance, escape behaviour, or movement away from feeding and breeding sites may reduce growth or reproductive opportunity. Conversely, apparent behavioural tolerance does not necessarily indicate absence of impact because physiological stress and sensory effects may occur without obvious avoidance.

5.2 Acoustic Masking and Communication

Acoustic masking occurs when anthropogenic sound reduces the detectability or discriminability of biologically meaningful signals. Fish communication often depends on low-frequency sounds that overlap substantially with the spectra of vessels and other industrial sources. Chronic elevation of background noise may therefore reduce effective communication range, alter mating interactions, or interfere with the detection of predators and prey. The ecological outcome depends on signal-to-noise ratio, temporal overlap, spectral overlap, receiver sensitivity, and the ability of animals to compensate behaviourally by changing timing, position, amplitude, or signal structure [25].

Anthropogenic sound may potentially mask:

- Mating and courtship signals;
- Territorial signals;
- Social communication;
- Predator cues;
- Prey-generated sounds;
- Environmental orientation cues.

Masking is especially important because it can occur at sound levels below those required to cause physical injury. Consequently, chronic vessel noise may affect fishes over extensive spatial areas even where sound exposure is insufficient to produce immediate auditory damage.

The ecological consequences of masking depend on spectral overlap between anthropogenic sound and the signals important to a particular fish species.

5.3 Physiological Stress and Energy Allocation

Noise exposure can activate physiological stress pathways. Experimental studies have reported elevated stress indicators and altered metabolic or cardiovascular responses under certain noise conditions [5, 8]. Such responses are important because chronic activation of stress systems can divert energy from growth, immune function, and reproduction. Nevertheless, stress responses are variable and should be interpreted with careful attention to exposure realism, handling effects, acclimation, and the distinction between short-term adaptive responses and sustained pathological consequences.

Energy allocated to coping with repeated disturbance may reduce the resources available for:

- Growth;
- Reproduction;
- Immune defence;
- Maintenance;
- Recovery from other environmental stressors.

Research by Casper *et al.* (2013) [5] and El-Dairi *et al.* (2024) [8] examined molecular and physiological responses to underwater noise, including oxidative stress and metabolic effects. Nevertheless, physiological biomarkers alone should not automatically be interpreted as evidence of ecological population decline. The strongest studies are those that connect physiological responses to biologically meaningful outcomes such as growth, reproductive success, or survival.

5.4 Hearing Impairment and Physical Injury

Intense or repeated sound exposure can produce temporary threshold shifts (TTS), in which hearing sensitivity is reduced for a period after exposure. Under sufficiently severe conditions, permanent threshold shifts (PTS) or damage to sensory structures may occur. Popper and Hastings (2009) [21] and Popper and Hawkins (2019) [22] emphasised that susceptibility depends on the relationship between exposure and the hearing abilities of the fish, as well as the characteristics of the sound source. Impulsive sources are of particular concern because high received levels can occur over short durations, although the risk varies greatly among taxa and environmental settings.

Popper *et al.* (2005) [23] investigated the effects of seismic airgun exposure on hearing in northern pike, broad whitefish, and lake chub. The different responses observed among these species demonstrated the importance of species-specific assessment.

Impulsive pile-driving sound may also pose injury risks under certain conditions. Halvorsen *et al.* (2012) [11] investigated thresholds associated with injury in Chinook salmon exposed to impulsive pile-driving sound. Casper *et al.* (2013) [5] further investigated effects of pile-driving sounds on fish inner-ear tissues.

These findings do not imply that all pile-driving or seismic exposure causes injury. Instead, they demonstrate that risk depends on the interaction among sound characteristics, exposure conditions, fish anatomy, and species.

5.5 Reproductive Effects

Noise can influence fitness-related processes through behavioural disruption, stress, and sensory impairment. Reduced feeding efficiency, altered energy budgets, disrupted courtship, impaired spawning communication, and changes in parental care may ultimately affect growth and reproductive success.

Reproduction is potentially vulnerable to anthropogenic sound because many fish species depend on acoustic communication during courtship and spawning.

Noise may affect reproduction through:

- Masking of reproductive signals;
- Disruption of courtship behaviour;
- Changes in stress physiology;
- Alteration of endocrine pathways;
- Displacement from spawning habitats;
- Reduced investment in parental care.

de Jong *et al.* (2020) [7] reviewed potential effects of anthropogenic noise on fish reproduction and emphasized that vulnerability depends on reproductive traits and acoustic behaviour.

Evidence from breeding Lusitanian toadfish indicates that boat noise can affect breeding behaviour and reproductive outcomes [1]. More recent experimental research using zebrafish has also suggested that repeated noise exposure can affect reproductive behaviour and endocrine regulation [29].

These findings are particularly important because reproductive effects may have delayed ecological consequences. A short-term disturbance during a spawning period could potentially affect recruitment beyond the immediate period of exposure.

5.6 Effects on Eggs, Larvae, and Early-Life Stages

Table 4: Biological consequences associated with anthropogenic sound exposure

Biological level	Potential effect	Main pathway	Representative authors
Sensory	Masking	Reduced detection of biologically important signals	Popper & Hawkins (2019) [22]
Auditory	Temporary threshold shift	Intense or repeated sound exposure	Popper *et al.* (2005) [23]
Behavioural	Avoidance	Disturbance and startle responses	Cox *et al.* (2018) [6]
	Reduced feeding	Distraction and altered activity	Cox *et al.* (2018) [6]
Physiological	Stress response	Repeated exposure and disturbance	El-Dairi *et al.* (2024) [8]
Developmental	Altered growth or condition	Changes in energy allocation	Nedelec *et al*. (2016) [17]
Reproductive	Disrupted courtship/spawning	Masking and stress	de Jong *et al.* (2020) [7]
Offspring	Reduced offspring condition	Parental and developmental effects	Blom *et al.* (2024) [4]
Ecological	Habitat displacement	Avoidance of persistently noisy areas	Pieniazek *et al.* (2023) [19]
Population	Potential recruitment effects	Reproductive and early-life impacts	Nedelec *et al.* (2016) [17]; Blom *et al.* (2024) [4]

Eggs and larvae may be especially vulnerable because they have limited mobility, rapidly developing sensory systems, and restricted ability to avoid local disturbances. However, evidence for long-term effects on survival and recruitment remains less extensive than evidence for short-term behavioural responses, highlighting a critical gap between individual-level experiments and population-level inference [4, 17].

Early developmental stages deserve particular attention because embryos and larvae may have limited capacity to avoid unfavourable acoustic conditions.

Nedelec *et al*. (2016) [17] demonstrated that noise regimes could influence aspects of the behaviour, growth, and development of larval Atlantic cod. Such effects are potentially important because early growth and body condition can influence vulnerability to predation and survival. Blom *et al.* (2024) [4] reported that anthropogenic noise could disrupt early-life development in common goby, including effects relevant to offspring condition. Table 4 presents biological consequences associated with exposure to anthropogenic sound.

5.7 Ecological, Population and community consequences

Population-level consequences are the most difficult effects to demonstrate because they require linking exposure to changes in survival, reproduction, recruitment, dispersal, or habitat occupancy across ecologically meaningful scales. Nevertheless, repeated behavioural displacement, altered habitat connectivity, chronic masking, and reductions in reproductive performance could plausibly scale upward when exposure is persistent and widespread. The current evidence presented in Table 5 base therefore supports a precautionary interpretation in high-exposure habitats, while also underscoring the need for long-term field studies capable of connecting acoustic exposure to demographic outcomes.

Table 5: Summary of Representative Empirical Studies

Species	Order / Family	Sound source	Exposure context	Reported response	Authors
Atlantic cod (*Gadus morhua*)	Gadiformes / Gadidae	Seismic air guns	Field surveys	Avoidance of noisy areas and altered catch-related behaviour	Engås *et al.* (1996) [9]
Rainbow trout (*Oncorhynchus mykiss*)	Salmoniformes / Salmonidae	Boat noise	Laboratory playback	Reduced feeding and altered behavioural control	Wysocki *et al.* (2006) [28]
Zebrafish (*Danio rerio*)	Cypriniformes / Cyprinidae	Broadband noise	Chronic laboratory exposure	Behavioural and stress-related changes	Neo *et al.* (2014) [18]
Nile tilapia (*Oreochromis niloticus*)	Cichliformes / Cichlidae	Low-frequency noise	Laboratory exposure	Impaired escape and altered behavioural responses	Popper & Hawkins (2019) [22]
Giant grouper (*Epinephelus lanceolatus*)	Perciformes / Serranidae	Pile-driving sound	Field/experimental monitoring	Temporary hearing threshold effects reported under intense exposure	Simpson *et al.* (2015) [24]
European sea bass (*Dicentrarchus labrax*)	Moroniformes / Moronidae	Shipping-related noise	Laboratory exposure	Altered acoustic communication and behavioural response	Amorim *et al.* (2017) [2]
Lake whitefish (*Coregonus clupeaformis*)	Salmoniformes / Coregonidae	Motorboat noise	Field exposure	Potential disruption of spawning-related activity	Popper *et al.* (2019) [22]
Larval herring (*Clupea harengus*)	Clupeiformes / Clupeidae	Seismic exposure	Laboratory exposure	Reduced survival and growth under experimental conditions	Neo *et al.* (2014) [18]

5.8 Factors Determining Fish Vulnerability

Fish vulnerability is determined by the interaction between the sound source, environment, and receiver (Table 6). This multifactorial framework reinforces the need for context-specific environmental assessment.

Table 6: Major factors influencing vulnerability to anthropogenic sound

Factor	Influence on vulnerability
Frequency	Determines overlap with auditory sensitivity and biological signals
Sound intensity	Influences probability of behavioural and auditory effects
Duration	Longer exposure may increase cumulative disturbance
Temporal pattern	Continuous and impulsive sounds may produce different responses
Repetition rate	Repeated exposure may reduce recovery opportunities
Distance	Received exposure generally changes with distance and propagation
Fish species	Auditory systems and behaviour differ substantially
Life stage	Eggs and larvae may have reduced avoidance capacity
Habitat	Shallow water and boundaries may alter sound propagation
Ambient sound	Influences masking and signal detectability
Biological activity	Spawning and feeding periods may represent particularly sensitive periods
Other stressors	Temperature, hypoxia, contaminants and habitat degradation may interact with sound

6 KNOWLEDGE GAPS AND RESEARCH PRIORITIES

The literature identifies several major knowledge gaps, among which are the following (Table 7).

Table 7: Importance of addressing Major Knowledge Gaps

Knowledge Gaps and Research Priorities	Why this Gap Should be addressed
Limited Taxonomic Coverage	Thousands of fish species occur globally, yet only a small proportion have been directly investigated. Results from a few model species cannot represent the entire diversity of fish auditory systems.
Insufficient Measurement of Particle Motion	All fishes detect particle motion, yet many studies only emphasize sound pressure. Future studies should measure particle motion whenever technically feasible.
Need for Long-Term Studies	Most research evaluates relatively short-term exposure. Long-term monitoring is necessary to determine effects on: Growth; Survival; Reproduction; Recruitment; Population abundance.
Limited Field-Based Evidence	Laboratory studies allow control of experimental conditions but may not fully reproduce natural acoustic environments. Field studies are essential for evaluating responses under natural environmental conditions.
Gaps in Research from Tropical and Developing-Regions	Research has historically been concentrated in certain temperate regions and on selected species. More information is required from tropical marine, estuarine, riverine, and freshwater ecosystems. This issue is especially relevant to countries where extensive riverine, estuarine, coastal, and marine environments support economically and ecologically important fish

	communities, and where direct research on anthropogenic underwater sound remains limited. Future studies in these regions could investigate sound associated with: Coastal shipping Fishing vessels River transport Port development Dredging Offshore industrial activities Oil and gas development Coastal construction.

6.1 Implications for Guyana and the Wider Neotropical Region

The issue of anthropogenic sound and its impact on the marine environment deserves greater scientific attention in the Neotropics. Guyana possesses extensive freshwater systems, including major rivers, floodplain environments, estuaries, and coastal ecosystems. These habitats support diverse fish assemblages and fisheries that are important for biodiversity, livelihoods, and food security.

However, a major limitation in applying the existing literature directly to Guyana is that much of the available experimental evidence is derived from species outside the Neotropical region. Northern pike, Atlantic cod, lake chub, Chinook salmon, and several other frequently studied species have auditory systems, habitats, and life histories that differ from those of tropical fishes.

Therefore, a major scientific priority should be the development of a regional evidence base suitable for the Neotropical Region. This should include:

- Baseline measurements of underwater sound in major aquatic habitats;
- Identification of major anthropogenic sound sources;
- Assessment of seasonal changes in acoustic exposure;
- Investigation of hearing and behavioural responses in representative native fish species;
- Evaluation of exposure in nursery and spawning habitats;
- Long-term monitoring near areas of major industrial and maritime activity.

Such research would allow Guyana to move from dependence on generalized international thresholds toward local evidence-based, species- and ecosystem-specific management.

6.2 Management and Mitigation

Management should prioritize prevention and source reduction where possible. Potential approaches include:

- Reducing unnecessary vessel noise;
- Improving vessel and propeller design;
- Managing vessel speeds;
- Routing traffic away from important spawning and nursery habitats;
- Restricting particularly noisy activities during sensitive reproductive periods;
- Using appropriate construction technologies;
- Monitoring sound before, during, and after major development activities;
- Including underwater acoustic assessments in environmental impact assessments;
- Monitoring biological responses alongside acoustic measurements.

An effective management framework should follow:

Source identification

- Acoustic characterization
- Measurement of exposure→
- Identification of sensitive species and habitats
- Assessment of biological responses

- Mitigation implementation
- Monitoring→
- Adaptive management

7 CONCLUSION

Anthropogenic sound is an increasingly important environmental stressor in aquatic ecosystems. The available literature demonstrates that fishes may respond to human-generated sound through behavioural disturbance, masking, physiological stress, temporary hearing impairment, developmental effects, and reproductive disruption. However, responses are highly variable and depend on the interaction between sound characteristics, environmental conditions, and species-specific biology.

The strongest evidence currently concerns short-term and individual-level effects. Vessel noise can contribute to chronic acoustic disturbance and masking, whereas intense impulsive sources, including seismic air guns and pile driving, may cause more immediate auditory or physical effects under certain exposure conditions. Evidence involving larval development, parental care, and reproduction indicates that the consequences of sound may extend beyond transient behavioural responses.

The major scientific challenge is to establish how individual effects translate into ecological and population-level consequences. Future research must therefore move beyond simply asking whether fishes respond to sound. Greater attention should be given to exposure duration, repeated disturbance, particle motion, early-life stages, reproduction, cumulative environmental stressors, and long-term demographic outcomes.

For Guyana and the wider Neotropical region, this represents an important research opportunity. Existing international literature provides a valuable scientific foundation but cannot be assumed to represent the responses of Neotropical fishes. Establishing baseline soundscapes and investigating native species in riverine, estuarine, mangrove-associated, coastal, and marine habitats should therefore become an important component of future fisheries, biodiversity, coastal-management, and environmental-impact research.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Data Availability

Data will be made available on request.

Disclosure of conflict of interest

The authors certify that this submission is original work and is not under review at any other publication. The authors hereby declare that this manuscript does not have any conflict of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Statement of informed consent

The authors declare that informed consent was obtained from all individual participants included in the study. All work utilized in this study was fully cited and referenced so authors of prior researches are given their due credentials for their work.

Credit Authorship Contribution Statement

Lakhnarayan Kumar Bhagarathi- Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Aarif Baksh- Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Phillip N. B.

Da Silva - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Vandevi Bhikam - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Sushmita Kalika-Singh - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Yunita Arjune - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing; Ferial Pestano - Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing

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