Aquatic biota is not exempt from Coronavirus infections: An overview

Núñez-Nogueira, G* and Granados-Berber, A.A.
Laboratorio de Hidrobiología y Contaminación Acuática, DACBioI Universidad Juárez Autónoma de Tabasco, Carretera Villahermosa-Cárdenas Km. 0.5., Villahermosa, Tabasco 86039, México. *Corresponding author: gabriel.nunez@ujat.mx (ORCID: 0000-0001-9217-6959).

Abstract
Coronaviruses are pathogens recognized for having an animal origin and commonly associated with terrestrial environments. However, although in few cases, there are reports of their presence in aquatic organisms like fish, crustaceans, waterfowls and marine mammals. None of these cases have even led to human health effects, when contact with these infected organisms, whether they are alive or dead. Aquatic birds seem to be the main group in carrying and circulating these types of viruses in healthy bird populations and play an important role in these environments.
Although the route of infection for CoVID-19 (Coronavirus disease 2019) by water or aquatic organisms, has not yet been observed in the wild, the relevance of its study is highlighted, because there are cases of other viral infections (no coronavirus), which are known to have been transferred to the human by aquatic biota. What is even better, it becomes encouraging to know that aquatic species shows very few cases in fishes, marine mammals, and crustaceans, and some other aquatic animals may also be a possible source of cure or treatment against coronaviruses, as some evidence with algae and marine sponges suggests.

Keywords: Coronavirus, aquatic organisms, fish, marine mammals, crustaceans, birds.

Declarations
Funding: Not applicable.
Conflicts of interest/Competing interests: The author declares no conflict of interest.
Availability of data and material: Not applicable.
Ethics approval: Not applicable
Consent to participate: Not applicable.
Consent for publication: Not applicable.
Code availability: Not applicable.
Authors’ contributions: G.N-N. contributed to the study conception and design, and A.A.G-B and G.N-N material preparation, data collection, analyses, and approved the final manuscript.
Acknowledgement
The author G.N-N recognizes the support provided by the PII SNI-UJAT program and the assistance of Enrique Núñez-Jiménez to improve this manuscript.

1. Introduction
The current Severe Acute Respiratory Syndrome coronavirus 2 (SARS-CoV-2) or CoVID-19 pandemic, as it is commonly known, brought society's interest in one of the families of high-risk pathological-infectious viruses, known as Coronavirus (CoVs)[1]. The impact that the CoVID-19 has had on human dynamics is undoubtedly enormous. The mortality and public health impacts caused by CoVID-19, caught the attention of scientists to try to slow down its effects and look for a vaccine. This virus is already present in every continent, and as previous events with other viruses such as SARS or HIV (Human Immunodeficiency Virus), humans will have to learn how to live with it. However, this situation also makes us wonder about what other organisms may be subject to coronavirus infection? Which organisms can be vectors or reservoirs? That is that they may have the virus in their body, transport it and spread it in other areas or to other organisms, without suffering the symptoms of the infection. Moreover, can the coronavirus infect and affect aquatic organisms? These questions, indeed some present in the scientific and non-scientific communities may eventually be answered in a particular way over time for SARS-CoV-2. However, at the moment, scientific efforts are focused on the public health aspects at the global level [2,3]. Thanks to previous studies on the subject, we can have access to information that allows us to understand more about the possible scenarios associated with these questions.
Moreover, to be able to make more specific approaches to the impact of SARS-CoV-2 on aquatic organisms, based on the general knowledge that is available on coronaviruses.

1.2 Coronavirus features
CoVs are pathogens associated with epithelial cells infections such as gastrointestinal (gastroenteritis) and respiratory (respiratory infections) [4–6]. Its structure consists of three components: 1) genetic material with which it replicates or reproduces within infected cells, known as RNA (ribonucleic acid of a chain between 26 and 32 kb in length), 2) an external protein that surrounds it known as caps (viral wrap) and 3) a membrane that surrounds and envelops the protein cover, which is covered in turn, with spicules that give the shape of a "crown", from which they are called coronavirus, and that allows them to recognize and come into contact with the membrane of the cell that will infect [7,8]. These spicules are called the "S" protein [7].

It is recognized that CoVs have its origin in bats, with several varieties or viral species depending on poly-protein or full genome analyses [8,9], which include some of the most toxic and lethal strains of recent decades. CoVs mainly affect terrestrial organisms, such as humans, bats, felines, camels and birds [8,10]; however, their potential to infect the aquatic life has been demonstrated.

Coronaviruses are part of the Family Coronaviridae of the Order Nidovirals, which in addition to infecting mammals and birds, have also been found in crustaceans, fish and marine mammals [6,8]. Four genera are recognized based on their phylogeny and genomic structure, from the subfamily Orthocoronavirinae, of which Alphacoronavirus,
**Betacoronavirus, Gammacoronavirus and Deltacoronavirus** stand out, for their ability to infect humans and non-human respiratory tracts, and other organisms at the digestive level (enteritis) [8]. Within this group of Nidovirals, we find viruses such as the widely known SARS-CoV and MERS-CoV (Middle East Respiratory Syndrome), both belonging to the genus *Betacoronavirus* and subgenus *Sarbecovirus* and *Merbecovirus*, respectively [6,8]. These two types of viruses are recognized as infectious of zoonotic origin, that implies a transmission from an animal, as a result of direct interactions with an animal carrying the infection. The other subfamily within the Coronaviridae is the *Torovirinae*, formed in turn by two genera, *Torovirus* and *Bafinivirus*, respectively. *Bafinivirus*, in fact, has been identified in a teleost fish [11,12].

### 2. Coronavirus and aquatic environments

Interest in virus transmissions in aquatic media focuses on those with public health relevance, which often enter natural water from treated and untreated wastewater discharges [4,13]. In the 1980s, it was recognized that as far as pathogenic viruses are concerned, more than 100 different types are excreted by man or by animals through their faeces [14]. The stool is one of the main materials for viruses transfer to water bodies. The transfer to the mouth as a result of poor hygiene, or the intake of contaminated water, allows viruses to enter the digestive system, infecting and replicating itself in the gastrointestinal tract, and then being expelled in large numbers again in the faeces produced by infected people or animals [15]. It is estimated that about 10 billion viral particles are present for every gram of excrement [16]. Sewages, especially in countries with limited capacities for treatment and adequate sanitization, poses a risk of contamination when discharged or overflowing into the bodies of natural water occurs [16]. Unfortunately, this scenario becomes more complicated considering that also hospital waste, biological-infectious and sanitary waste (intimate towels, mouth covers, gauze, body protectors among others), can eventually reach lakes, lagoons, rivers and seas, due to their mishandling as solid waste, becoming vectors of viruses towards the aquatic environment. Recently, a study has shown the presence of SARS-CoV-2 from the waste discharge activities of infected communities [17]. For CoVs in general, it is reported that they can continue active or infectious for up to several weeks in water, including wastewaters [18]. Thus, viruses can come into contact with free-living aquatic organisms or in aquaculture farms and then be transmitted to humans when they become pets or food, and that, in the near future, it could be the way for new coronavirus outbreaks, which will need to be evaluated particularly for CoVID-19.

Some CoVs transmitted through contaminated food or water include *Alphacoronaviruses* such as 229E and NL63 or *Betacoronaviruses* such as OC43 and HKU1 (not well-known frequencies) and SARS (with occasional frequencies) [5]. Infections related to contaminated water can have various routes of contagion that may include aspiration, inhalation of aerosol droplets, penetration by the skin or mucous membranes, as well as by intake [19].

The presence of CoVs in natural waters has been determined with low percentages, compares to another type of viruses; however, they have been detected recently, as is the case of the Ilé river basin in Kazakhstan [20].
2.1 CoVs and aquatic organisms

Studies focusing on viral infections in aquatic organisms have targeted mainly those species of commercial importance and especially those of aquaculture exploitation [21], or those associated with captivity and tourism industry, such as marine mammals in aquariums and water parks [22].

Within the CoVs that have been identified in aquatic organisms and also associated to important pathological infections, we find those that affect crustaceans, fish, marine mammals (Table 1) and waterfowl (Table 2 and 3). No mollusc infections by CoVs have been reported so far.

2.1.1 Crustaceans

Crustaceans are recognized as a group capable of accumulating in their exoskeleton or body cover human pathogens. However, their role in the transmission of diseases to humans has not been proven [23], perhaps by the culinary habits and customs of removing body covers before ingesting them. In shrimps, the "Yellow head virus" or YHV [24], was reported in 1990 (Table 1) in East and Southeast Asia, affecting *Penaeus monodon* shrimp farmed. There are unconfirmed reports in Mexico for *P. Stylirostris* and *P. vannamei* [24–26]. Genetic studies showed that YHV had undergone significant recombination processes, apparently attributable to international trade with wild and farmed shrimp in the Asia-Pacific region, promoting a faster genetic diversity of the virus, as a result of several recombination events [27].

2.1.2 Fishes

In the case of fish, viruses of the *Bafinivirus* group have been reported [6,12,28,29]. There are cases since the late 1980s, where CoVs have been identified, particularly in Japan by 1988, in the common carp (*Cyprinus carpio*), widely cultivated and consumed in the world [30,31]. Production involvements reached 70% mortality within 20 days, with pathological damage including renal and hepatic tubular necrosis, as well as damage to renal hematopoietic tissue [28], skin and abdomen bleeding [12]. However, *Bafiniviruses*, together with *Gammacoronaviruses* detected in marine mammals, are usually found mainly in the digestive tract of the host or infected organisms [5]. It is also recognized that the first report of CoVs was in another European cyprinid known as white bream (*Blicca bjoerkna*), which showed a bacilliform structure, related to the viruses of the subfamily Torovirinae, giving rise to a new genus defined as *Bafinivirus* [12]. Most recently this genus has been reported in *Pimephales promelas* or bighead face fish [32,33] and on the salmon *Oncorhynchus tshawytscha* [34], identified as two different types of *Bafinivirus* (Table 1).

Some Chinese electronic media have stated that CoVID-19 cannot be transmitted through fish, under the argument of the virus's thermo-tolerance and the low body temperature of fish, compared to those of mammals [35]. However, this must be confirmed. Recent and specific tests of SARS-CoV-2 tolerance to thermal gradients have demonstrated tolerance between 4°C and 20°C in the air [36]. This temperature range is below the human body temperature (36.6°C), which are resisted and tolerated by SARS-CoV-2 during human infections. In drinking water, its dispersion seems to decrease at 23°C [37]. In addition, we must recognize that this would have relevant implications for tolerance, if we...
consider that fish and crustaceans are ectothermic (some fishes can be heterothermic, like tuna), that is, their body temperature is equal to that of the environment around them [38], and fish that have shown the presence of CoVs have a tolerance to a wide range of temperatures, from temperate to warm conditions (like cyprinid fish that lives or reproduces between 17°C and 30°C [39]), which in the case of the CoVID-19, could allow its incorporation by fish, just considering their body temperature as a limit factor for its infection. On the other hand, Peneid shrimps are tropical (between 24°C and 32°C [40]), and marine mammals regulate body temperatures in a lower range than humans (29-32°C [41]). Despite this, marine mammals have developed CoVs infections, as can be seen in Table 1. Under this evidence, the body temperature would not be a limiting factor on the possible future infection of SARS-CoV-2 to crustaceans, fish and marine mammals, or at least once they have already entered the body of the organism.

2.1.3 Waterfowl.

Of the groups of animals associated with aquatic environments, birds appear to be the group with the higher diversity of CoVs, with at least 96 genetically identified varieties found during this review (Table 2 and 3), within two of the four genera (71 Gammacoronavirus and 13 Deltacoronavirus, respectively) of the subfamily Orthocoronavirinae [42]. Different types of birds, such as gulls (Larus hyperboreus, L. galaceseus), geese (Branta bernicla, Anser caerulescens), spatulas (Platalea minor), herons (Ardea cinerea, Ardeola bacchus), cormorants (Phalacrocorax carbo) and ducks (Anus Americana, A. crecca, A. clypeata, A. penelope, A. acuta, Dendrocynyga javanica) are confirmed carriers of CoVs. The ducks of the genus Anas sp. and Anser sp. are the most represented and capable of carrying even strains of SARS-CoV. Particularly noteworthy are Anas domestica, Anas platyhrynchos and Anser anser (Table 2).

Some birds, such as cormorant and ducks are migratory, and that would allow wide geographical distribution of these types of viruses. Although no reports of human infection originated from waterfowl have been detected, the ecological study of these correlation becomes indispensable, to understand better the relationship of birds and CoVs, and their epidemiology among birds and other species within their ecosystems [42].

2.1.4 Marine mammals.

Regarding marine mammals, the first report of CoVs dates back to the 1970s associated with the death of several seals (Phoca vitulina) in a Florida aquarium [43] and other free-living pinnipeds off the coast of California [44]. This infection was known as HSCO (Harbor Seal coronavirus), identified as deadly haemorrhagic pneumonia caused by Alphacoronavirus group [44]. Years later, in 2008, the presence of other CoVs was detected in a beluga whale (Delphinapterus leucas) under captivity (BWCov SW1) [9,45]. In 2014, the presence of CoVs was detected in faeces from bottlenose dolphins [9], from the Indo-Pacific (Tursiops aduncus), which was called BdCoV HKU22 (Bottlenose dolphin CoV). These latter two were recognized within the Gammacoronavirus group, which caused viral bronchitis to those infected animals [9]. The gregarious behavior of several marine mammal species may promote the contagion and dispersal of these types of pathogens in wild populations, so their monitoring becomes essential and necessary for their health and avoid further transmission to others aquatic organisms.
Gammacoronavirus detected in marine mammals, unlike *Bafinivirus* in fish, can also be found in the respiratory tracts of terrestrial and marine mammals and not only in the digestive tracks [5]. Viruses such as influenza A and B have been reported in mammals such as seals and cetaceans [5,22], which have come to be considered as reservoirs and vectors towards humans [5]. This scenario opens up the possibility that other viruses, including CoVs, could be transmitted to humans when interacting and coming into contact with seals, sea lions and dolphins in water parks and aquariums. Working with infected wildlife, or using them as food sources, especially in communities such as Asian ones, might also be another route of transmission. These leads us to one of the main questions in case of the SARS-CoV-2 infects an aquatic ecosystem…, would SARS-CoV-2 from aquatic organisms infect humans?.

3.- Virus infections to humans from aquatic organisms

During this review, no published studies on the actual risk of SARS-CoV-2 contagion from aquatic organisms were found. There is a history of other viral respiratory infections transmitted to humans from either wild or captive animals [15,22]. That is the case with influenza-A, caused by the H7N7 virus, in people infected during a necropsy performed to a seal [43], or by coming into contact with the sneeze of a seal in captivity [22], causing conjunctivitis, rather than typical influenza or respiratory disease. A similar case has also been identified for Influenza B [5,22]. Moreover, a historical review carried out by Petrovic et al. [15], has shown numerous viral outbreaks (not CoVs related) associated with shellfish. These outbreaks, included human enteric viruses, mainly those of type NoV (norovirus), HAV (hepatitis virus A), EV (Enterovirus), HAdV (human adenovirus) and HRV (human rotavirus) are reported in shellfish in different countries, but not CoVs. Oysters and clams have been associated with NoV and HAV between 1976 and 1999, in the United States alone. The presence of these viruses has also been identified in mollusces in Europe, both in fish and sea markets and in oyster farms associated with human enteric viruses between 1990 and 2006 [46,47] and all are good examples of food as a source of viral infections. For the World Health Organization and the Food and Agriculture Organization Joint Committee, coronaviruses related to Severe Acute Respiratory Syndrome (SARS-CoV) are viruses of concern by contaminated food [48]. There are other types of water-viruses associated with birds, such as H5N1 avian influenza and avian influenza A1, also highly infectious, and recognized for their transmission to humans from duck meat and blood [49,50]. Due to these examples, there are required extensive monitoring studies since ducks are one of the main groups of birds capable of carrying CoVs (Table 2).

At the moment, as long as there are no more significant scientific elements to be certain of the non-spread of the SARS-CoV-2 pandemic through natural waters and aquatic organisms, it is best to follow the indications that the health authorities have been issuing in this regard. These indications highlight those made by the World Health Organization [51], which recommends avoiding unprotected contact with wild and farm animals, and has even been recommended not to approach public markets where wild animals are under sale, both live and slaughtered [8].

4.- Conclusions

The presence of CoVs in aquatic environments is a reality, which has demonstrated its ability to be transmitted to organisms in wildlife, aquaculture farms and animals under captivity. The presence observed in farmed fish such as carp, in farmed and wild populations of penaeid shrimp, although they have not reported significant effects or...
consequences on human health, could be of potential risk in the near future. Knowledge of other cases such as marine mammals, where seals have shown to be carriers of respiratory infections, which have eventually been transmitted to humans, with effects on eye membranes, even in infections as dangerous as influenza diseases, must be taken in consideration. Waterfowl show to be a natural reservoir, mainly ducks, which, due to their migratory behaviors, deserve to be studied in more detail. The high adaptive capacity of viruses, the wide distribution and recombination potential of their genetic material, could be factors that favor their eventual pathogenicity through aquatic environments. Although molluscs are not infected with CoVs, their antecedents as vectors of other viruses, make them suitable for monitoring for possible future infections.

5.- Further considerations for CoVs and aquatic biota

The efforts of the scientific community will continue over the coming years to learn more about CoVID-19. Genetic adaptation, including mutation and recombination, identify routes of zoonotic (animal) origin, new vector organisms (birds, mammals, fish, molluscs or crustaceans), animal-human transmission events, wild natural storage and contagion risks, which will allow effective and realistic programmes to control the transmission of coronaviruses, particularly SARS-CoV-2. It is recognized that viral genotypes with epidemiological potential can become very variable, as a result of their genetic characteristics, which allow them to endure and survive, as well as spread and even mutate along trophic chains [23]. It is encouraging to know that even other aquatic organisms, such as seaweed or sponges, could play a key role in the treatment of CoVs infections. It has been observed through laboratory tests with Halimeda tuna algae, a natural product known as diterpene aldehyde or halitunal [52], with an antiCoV effect. Other examples are the sponge Mycale sp, which produces a substance called micalamide A, both with antiviral capacity against the A59-CoV of murine or rodent origin [53,54]. Another good example is the Axinella corrugata sponge that produces an ethyl ester of esculetin-4-carboxylic acid against SARS-CoV [55]. These substances together with other products of natural origin [54,56], could be the sources of some control against to coronavirus like SARS-CoV-2 in the future.

Although some scientists speculate that CoVs will not last long in the environment, especially in tropical and subtropical environments [57], due to their intolerance to high temperatures, the diversity and presence of CoVs in aquatic organisms should be monitored. Their varieties identified adequately in infected wild populations, to better understand their infectious potential and avoid future outbreaks in the wild, which eventually could also reach humans.

References

1. Burki T. Outbreak of coronavirus disease 2019. Lancet Infect Dis. 2020;20:292–3. http://dx.doi.org/10.1016/S1473-3099(20)30076-1

2. Haleem A, Javaid M, Vaishya R, Deshmukh SG. Areas of academic research with the impact of COVID-19. Am J Emerg Med. 2020;5:–7.

3. Qu G, Li X, Hu L, Jiang G. An imperative need for research on the role of environmental factors in transmission of novel coronavirus (COVID-19). Environ Sci Technol. 2020;54:3730–2.

4. Bosch A, Pintó RM, Le Guyader FS. Viral contaminants of molluscan shellfish: Detection and characterisation.
5. Boussettine R, Hassou N, Bessi H, Ennaji MM. Waterborne transmission of enteric viruses and their impact on public health. Emerg. Reemerging Viral Pathog. Vol. 1 Fundam. Basic Virol. Asp. Human, Anim. Plant Pathog. Elsevier Inc.; 2019. http://dx.doi.org/10.1016/B978-0-12-819400-3.00040-5
6. de Groot R, Baker S, Baric R, Enjuanes L, Gorbunov Y, Holmes K, et al. Part II – The positive sense single stranded RNA viruses family Coronaviridae. In: King AMQ, Adams MJ, Carstens EB, Lefkowitz EJ, editors. Virus Taxon ninth Rep Int Comm Taxon Viruses. London: Academic Press; 2012. p. 806–28.
7. Avendaño-López C. Aportaciones de las ciencias biomédicas en el estado de alarma motivado por la pandemia del virus COV-2. An la Real Académia Nac Farm. 2020;86:9–17.
8. Malik YS, Sircar S, Bhat S, Sharun K, Dhama K, Dadar M, et al. Emerging novel coronavirus (2019-nCoV)—current scenario, evolutionary perspective based on genome analysis and recent developments. Vet Q. Taylor & Francis; 2020;40:68–76. https://doi.org/10.1080/01652176.2020.1727993
9. Woo PCY, Lau SKP, Lam CSF, Tsang AKL, Hui S-W, Fan RYY, et al. Discovery of a novel bottlenose dolphin coronavirus reveals a distinct species of marine mammal coronavirus in Gammacoronavirus. J Virol. 2014;88:1318–31.
10. Kasmi Y, Khatabi K, Souiri A, Ennaji MM. Coronaviridae: 100,000 years of emergence and reemergence. In: Ennaji MM, editor. Emerg Reemerging Viral Pathog Vol 1 Fundam Basic Virol Asp Human, Anim Plant Pathog. Netherlands: Academic Press; 2019. p. 127–49.
11. Granzow H, Weiland F, Fichtner D, Schütze H, Karger A, Mundt E, et al. Identification and ultrastructural characterization of a novel virus from fish. J Gen Virol. 2001;82:2849–59.
12. Leong JC. Fish Viruses. Encycl. Virol. Elsevier Ltd; 2008. p. 227–34.
13. Roa VC, Melnick JL. Environmental virology. Berkshire: Van Nostrand Reinhold Co. Ltd.; 1986.
14. Melnick JL. Etiologic agents and their potential for causing waterborne virus diseases. Monogr Virol. Basel, Switzerland: Karger and Basel; 1984;15:1–16.
15. Petrović T, D’Agostino M. Viral contamination of food. Antimicrob Food Packag. 2016;65:65–79.
16. Farthing MJG. Viruses and the Gut. Walwyn Garden City, Hertfordshire: Smith Kline & French LTD.; 1984.
17. Lesté-Lasserre C. Coronavirus found in Paris sewage points to early warning system. Science (80–). 2020.
18. Casanova L, Rutala WA, Weber DJ, Sobsey MD. Survival of surrogate coronaviruses in water. Water Res. 2009;43:1893–8. http://dx.doi.org/10.1016/j.watres.2009.02.002
19. Natarajan P, Miller A. Recreational infections. In: Cohen J, Powerly WG, Opal SM, editors. Infect Dis (Auckl) [Internet]. Fourth. London: Elsevier Ltd; 2017. p. 643-646.e1. http://dx.doi.org/10.1016/B978-0-7020-6285-8.00071-X
20. Alexyuk MS, Turmagambetova AS, Alexyuk PG, Bogoyavlenskiy AP, Berezin VE. Comparative study of viromes from freshwater samples of the Ile-Balkhash region of Kazakhstan captured through metagenomic analysis. Virus Dis. 2017;28:18–25.
21. Ahne W. Viral infections of aquatic animals with special reference to Asian aquaculture. Annu Rev Fish Dis. 1994;4:375–88.
22. Shapiro DS. Infections acquired from animals other than pets. In: Cohen J, Powderly WG, Opal SM, editors. Infect Dis (Auckl). Fourth Edi. Elsevier Ltd; 2017. p. 663-669.e2. http://dx.doi.org/10.1016/B978-0-7200-6285-8.00074-5

23. Bosch A, Pintó RM, Guix S. Foodborne viruses. Curr Opin Food Sci. 2016;8:110–9.

24. Walker PJ, Cowley JA, Spann KM, Hodgson RAJ, Hall MR, Withychumnarnkul B. Yellow head complex viruses: transmission cycles and topographical distribution in the Asia-Pacific region. In: Browdy CL, Jory DJ, editors. new wave Proc Spec Sess Sustain Shrimp Cult Aquac 2001. Baton Rouge: World Aquaculture Society; 2001. p. 292–302.

25. Chantanachookin C, Boonyaratpalin S, Kasornchandra J, Direkbusarakom, S, Ekpanithanpong, U, Supamataya K, Sruiaratranta S, Flegel TW. Histology and ultrastructure reveal a new granulosis-like virus in Penaeus monodon affected by yellow-head disease. Dis Aquat Org. 1993;17:145–57.

https://pdfs.semanticscholar.org/6496/5bdc22dbbed904479487025c5003042256e.pdf

26. De la Rosa-Velez J, Cedano-Thomas Y, Cid-Beccera J, Mendez-Payan JC, Vega-Perez C, Zambrano-Garcia, J. Bonami JR. Presumptive detection of yellow head virus by reverse transcriptasepolymerase chain reaction and dot-blot hybridization in Litopenaeus vannamei and L. stylirostris cultured on the Northwest coast of Mexico. J Fish Dis. 2006;29:717–26.

27. Walker PJ, Winton JR. Emerging viral diseases of fish and shrimp. Vet Res. 2010;41.

28. Sano T, Yamaki T, Fukuda H. A novel carp coronavirus: characterization and pathogenicity. Fish Heal Conf. Vancouver, Canada; 1988. p. 160.

29. Schütze H. Coronaviruses in aquaculture. In: Kibenge F, Godoy M, editors. Aquac Virol. Amsterdam: Elsevier Inc.; 2016. p. 327–35. http://dx.doi.org/10.1016/B978-0-12-801573-5.00020-6

30. Miao W. Aquaculture production and trade trends: carp, tilapia and shrimp Weimin Miao , FAO RAP. 2015.

31. Karnai L, Szucs I. Outlooks and perspectives of the common carp production. Ann Polish Assoc Agric Agribus Econ. 2018;XX:64–72.

32. Batts WN, Goodwin AE, Winton JR. Genetic analysis of a novel nidovirus from fathead minnows. J Gen Virol. 2012;93:1247–52.

33. Iwanowicz LR, Goodwin AE. A new bacilliform fathead minnow rhabdovirus that produces syncytia in tissue culture. Arch Virol. 2002;147:899–915.

34. Lord SD, Raymond MJ, Krell PJ, Kropinski AM, Stevenson RMW. Novel chinook salmon bafinivirus isolation from ontario fish health monitoring. Proc Seventh Int Symp Aquat Anim Heal. Portland, Oregon; 2014. p. 242.

35. Youdao N. Can freshwater fish transmit novel coronavirus? Chinese W. 2020;19–20. Available from: //covid-19.chinadaily.com.cn/5e61f275a31012821727c689%0ACan

36. Casanova LM, Jeon S, Rutala WA, Weber DJ, Sobsey MD. Effects of air temperature and relative humidity on coronavirus survival on surfaces. Appl Environ Microbiol. 2010;76:2712–7.

37. Araujo MB, Naimi B. Spread of SARS-CoV-2 Coronavirus likely to be constrained by climate. medRxiv. 2020;2020.03.12.20034728.

38. Eckert R, Randall D, Augustine G. Fisología animal: Mecanismos y adaptaciones. Third Edit. Madrid, España: McGraw-Hill-Interamericana; 1990.
39. Peteri A. *Cyprinus carpio* (Linnaeus, 1758). In: Crespi V, New M, editors. Cult Aquat species fact sheets. Rome: FAO; 2009. p. 1–15. Available from:
http://www.fao.org/tempref/FI/CDrom/aquaculture/11129m/file/es/es_commoncarp.htm

40. Fenucci JL. Manual para la cría de camarones peneidos. FAO. Brasilia, Brasil: FAO; 1988. Available from:
http://www.fao.org/docrep/field/003/AB466S/AB466S04.htm

41. Melero M, Rodríguez-Prieto V, Rubio-García A, García-Parraga D, Sánchez-Vizcaino JM. Thermal reference points as an index for monitoring body temperature in marine mammals. BMC Res Notes. BioMed Central; 2015;8:411.

42. Chu DKW, Leung CYH, Gilbert M, Joyner PH, Ng EM, Tse TM, et al. Avian coronavirus in wild aquatic birds. J Virol. 2011;85:12815–20.

43. Bossart GD, Schwartz JC. Acute necrotizing enteritis associated with suspected coronavirus infection in three harbor seals (*Phoca vitulina*). J Zoo Wildl Med. 1990;21:84–7.

44. Kydyrmanov AI, Karamendin KO. Viruses of marine mammals and metagenomic monitoring of infectious diseases. Bull Natl Acad Sci Repub Kazakhstan. 2019;4:147–53.

45. Mihindukulasuriya KA, Wu G, St. Leger J, Nordhausen RW, Wang D. Identification of a novel coronavirus from a Beluga whale by using a panviral microarray. J Virol. 2008;82:5084–8.

46. Boxman ILA, Tilburg JJHC, te Loekte NAJM, Vennema H, Jonker K, de Boer E, et al. Detection of noroviruses in shellfish in the Netherlands. Int J Food Microbiol. 2006;108:391–6.

47. Boxman ILA. Human enteric viruses occurrence in shellfish from european markets. Food Environ Virol. 2010;2:156–66.

48. FAO/WHO. Viruses in food: Scientific advice to support risk management activities. Rome; 2008.

49. EFSA. Scientific Opinion on an update on the present knowledge on the occurrence and control of foodborne viruses. EFSA J. 2011;9:1–96.

50. Tumpey TM, Suarez DL, Perkins LEI, Senne DA, Lee J, Lee YJ, et al. Evaluation of a high-pathogenicity H5N1 avian influenza A virus isolated from duck meat. Avian Dis. 2003;47:951–5.

51. WHO. Novel coronavirus (2019-nCoV) advice for the public. 2020. Available from:
https://www.who.int/emergencies/diseases/novel-coronavirus-2019

52. Abad Martinez MJ, Bedoya Del Olmo LM, Bermejo Benito P. Natural marine antiviral products. Stud Nat Prod Chem. 2008;35:101–34.

53. Koehn FE, Gunasekera SP, Niel DN, Cross SS. Halitunal, an unusual disterpene aldehyde from the marine alga *Halmeda tuna*. Tetrahedron Lett. 1991;32:169–72.

54. Donia M, Hamann MT. Marine natural products and their potential applications as anti-infective agents. Lancet Infect Dis. 2003;3:338–48.

55. De Lira SP, Seleghim MHR, Williams DE, Marion F, Hamill P, Jean F, et al. A SARS-coronovirus 3CL protease inhibitor isolated from the marine sponge *Axinella cf. corrugata*: Structure elucidation and synthesis. J Braz Chem Soc. 2007;18:440–3.

56. Islam MT, Sarkar C, El-Kersh DM, Jamaddar S, Uddin SJ, Shilpi JA, et al. Natural products and their derivatives against coronavirus: A review of the non-clinical and pre-clinical data. Phyther Res. 2020;
57. Booth M. Climate change and the neglected tropical diseases. 1st ed. Rollinson D, Stothard R, editors. Adv. Parasitol. Elsevier Ltd.; 2018. Available from: http://dx.doi.org/10.1016/bs.apar.2018.02.001

58. Miyazaki T, Okamoto H, Kageyama T, Kobayashi T. Viremia-associated ana-aki-byo, anew viral disease in color carp Cyprinus carpio in Japan. Dis Aquat Organ. 2000;39:183–92.

59. Nollens HH, Wellehan JFX, Archer L, Lowenstein LJ, Gulland FMD. Detection of a respiratory coronavirus from tissues archived during a pneumonia epizootic in free-ranging pacific harbor seals Phoca vitulina richardsii. Dis Aquat Organ. 2010;90:113–20.

60. Shi Z, Hu Z. A review of studies on animal reservoirs of the SARS coronavirus. Virus Res. 2008;133:74–87.

61. Barbosa CM, Durigon EL, Thomazelli LM, Ometto T, Marcatti R, Nardi MS, et al. Divergent coronaviruses detected in wild birds in Brazil, including a central park in São Paulo. Brazilian J Microbiol. Brazilian Journal of Microbiology; 2019;50:547–56.

62. Hepojoki S, Lindh E, Vapalahti O, Huovilainen A. Prevalence and genetic diversity of coronaviruses in wild birds, Finland. Infect Ecol Epidemiol. Taylor & Francis; 2017;7. Available from: https://doi.org/10.1080/20008686.2017.1408360

63. de Sales Lima FE, Gil P, Pedrono M, Minet C, Kwiatak O, Campos FS, et al. Diverse gammacoronaviruses detected in wild birds from Madagascar. Eur J Wildl Res. 2015;61:635–9.
Table 1. Coronavirus found in aquatic organisms. Taxonomical groups, according to de Groot et al. [6] and Kasmi et al. [10].

| Group       | Genus       | CoV type       | Host                          | Health Effects                                      | Year  | Reference |
|-------------|-------------|----------------|--------------------------------|-----------------------------------------------------|-------|-----------|
| **Order**   | **Nidovirales** | **Suborder**   | **Cornivirinea** | **Family** | **Coronaviridae** | **Coronavirus(?)*** | **Carp CoV** | Common carp (Japan) | Erythema, necrosis (abdomen and liver) | 1988 | [21,29] |
|             |             | **Coronavirus(?)*** | **Carp Viremia-Associated Ana-Ki-Byo** | **Common carp (Japan)** | **Dermal ulcerations, necrotic lesion.** | **Found in spleen and hematopoietic tissue** | 1997-1998 | [29,58] |
| **Suborder** | **Coronavirinae** | **Family** | **Coronaviridae** | **Subfamily** | **Orthocoronavirinae** | **Alphacoronavirus** | **HsCoV** | Harbor seals (Aquatic Park, Florida, USA) | Acute enteritis, pulmonary edema | 1987 | [43] |
|             |             | **Betacoronavirus** | **Not reported** | **Gammacoronavirus** | **BWCoVSW1** | Beluga whale (Aquatic Park, California, USA) | Hepatic necrosis and pulmonary disease | 2008 | [6,45] |
|             |             | **Deltacoronavirus** | **Not reported** | **Torovirinae** | **Toriavirus(?)*** | **CIVH 33/86** | Grass carp (Hungary) | Not known | 1986 | [29] |
|             |             | **Bafinivirus** | **WBV DF24/00** | **Okavirus** | **YHV (Yellow Head Virus)** | **Chinook Salmon** | **Bafinivirus** | **Chinook salmon (Ontario, Canada)** | Not known | 2014 | [29,34] |
|             |             | **FHMNV** | Fathead minnow fish (Arkansas, USA) | Eyes and skin haemorrhage, tissue lesions (spleen, liver and kidney) | 1997 | [32,33] |

*still unclassified.
Table 2. Coronavirus found in waterfowl of the Order Anseriformes.

| Order     | Genus  | Specie        | Type of bird          | Type of CoV                          | References |
|-----------|--------|---------------|-----------------------|--------------------------------------|------------|
| Anseriformes | *Anas* | *domestica*   | Duck                  | Gamma (SARS-CoV)                     | [60]       |
|           |        | *platyrhynchos* |   Spotbill duck       | Gamma (SARS-CoV)                     | [60]       |
|           |        | *americana*   | American wigeon       | Delta (JQ065048.1)                   | [61]       |
|           |        | *crecca*      | Common teal           | Gamma (J0109, J0121, J0126, J0559, J0579, J1393); Delta (J1420) | [42,62,63] |
|           |        | *clypeata*    | Northern shoveler     | Gamma (K547, K554, K561, K589, K595, J0554, J0807, J1300, J0901, J1491); Delta (J0590) | [42,63]    |
|           |        | *penelope*    | Euroasian wigeon      | Gamma (K596, J0588, J1561)           | [42]       |
|           |        | *acuta*       | Northern pintail      | Gamma (J1375, J1393, J1404, J1407, J1435, J1616, J1451, PBA-10, PBA-15, PBA-16, PBA-25, PBA-37, PBA-124) | [42,62,63] |
|           |        | *erythrorhyncha* | Red-billed duck      | Gamma (KM093874, KM093875, KM093876, KM093877) | [63]       |
|           | *Clangula* | *hyemalis*    | Long-tail teal        | Gamma (KM093880)                     | [61]       |
|           | *Cygnus* | *cygnus*      | Whooper swan          | Gamma (Fin14395)                     | [62]       |
|           | *Dendrocygna* | *javanica*   | Lesser whistling duck | Gamma (Fin4983)                     | [62]       |
|           | *Aythya* | *fuligula*    | Tufted duck           | Gamma (KH08-0852)                    | [42,61]    |
|           | *Anser* | *caerulescens* | Snow goose            | Gamma (KM093872, KM093873, KM093878) | [63]       |
|           |        | *anser*       | Greylag goose         | Gamma (WIR-159)                      | [42,61]    |
|           |        | *cygnoides*   | Swan goose            | Gamma (SARS)                         | [60]       |
|           |        |              |                       | (DPV_5, DPV_10)                      | [61]       |
|           | *Branta* | *bernicla*    | Brent goose           | Gamma (KR-69, KR-70, KR88)           | [42,61,63] |
Table 3. Gammacoronavirus and Deltacoronavirus reported in aquatic birds.

| Order            | Genus       | Specie     | Type of bird         | Type of CoV                     | References          |
|------------------|-------------|------------|----------------------|---------------------------------|---------------------|
| **Pelecaniformes** |            |            |                      |                                 |                     |
|                  | Ardeola     | bacchus    | Pond heron           | Delta (KH08-1475, KH08-1474)    | [42]                |
|                  | Ardea       | cinerea    | Gray heron           | Delta (K581, K513)              | [42]                |
|                  | Bubulcus    | ibis       | Heron                | Gamma (KM093897)                | [61,63]             |
|                  | Platalea    | minor      | Black-faced spoonbill | Delta (J0569)                  | [42]                |
|                  | Phalacrocorax | carbo     | Great cormorant      | Delta (J0982, J1517)            | [42]                |
| **Gruiformes**   | Rallus      | madagascariensis | Madagascar rail   | Gamma (KM093896)                | [63]                |
|                  | Porphyryla  | alleni     | Allen’s gallinule    | Gamma (KM093890, KM093891, KM093892, KM093893, KM093894) | [61,63]             |
|                  | Gallinula   | chloropus  | Common moorhen       | Gamma (KM093881, KM093885, KM093887, Delta (JQ065049.1)) | [61,63]             |
| **Charadriiformes** | Charadrius | pecuarius  | Kittlitz’s plover    | Gamma (KM093879, KM093883, KM093884) | [61,63]             |
|                  | Gallinago   | macrdocyta | Madagascan snipe     | Gamma (KM093888, KM093889, KM093895) | [63]                |
|                  | Calidris    | mauri      | Wester sandpiper     | Gamma (KR-28)                   | [61]                |
|                  |             | ptilocnemis | Rock sandpiper      | Gamma (CIR-66187, CIR-665821, CIR-665828) | [42,61,63]         |
|                  |             | alba       | Sanderling           | Gamma (PNLP100)                 | [61]                |
|                  |             | fusaccollis | White-rumped sandpiper | Gamma (PNLP159)               | [61]                |
|                  | Larus       | sp         | Gull                 | Delta (JX548304)                | [61]                |
|                  |             | argentatus | Hearing gull         | Gamma (Fin9211, Fin10877, Fin10879, Fin12822, Fin13125) | [62]                |
|                  |             | hyperboreus | Glaucous gull        | Gamma (PBA-173)                 | [42]                |
|                  |             | fuseus     | Lesser Black-back gull | Gamma (Fin10059)             | [62]                |
|                  |             | glaucescens | Glaucous-winged gull | Gamma (CIR-66002, GU396682)      | [42]                |
|                  | Chroicocephalus | ridibundus | Black-headed gull    | Gamma (CIR-66187, GU396679, GU396680, GU396683, KX588674, Fin10083) | [42,62]         |
|                  | Rostratula  | benghalensis | Great Painted-snipe  | Gamma (KM093883)               | [61]                |
|                  | Rynchops    | niger      | Black skimmer        | Delta (PNLP115)                 | [61]                |