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Review

The Prevalence of Viruses Related to the Production of Mussels and Oysters in Saldanha Bay: A Systematic Review

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Abstract: The disposal of treated and untreated sewage near shellfish harvesting areas is a global concern. Discharged sewage may be contaminated with enteric viruses present in human faeces. Bivalve molluscs, in turn, act as vectors for enteric viruses through bioaccumulation and retention of these viruses during the filter-feeding process, resulting in outbreaks of infections due to the consumption of contaminated shellfish. This review was conducted using peer-reviewed articles published from 2012 until September 2022, obtained from online databases such as Google Scholar, Scopus, and Science Direct, highlighting the challenges that the shellfish industry is faced with concerning pollutants ending up in the shellfish production areas. Developed countries have made some advancements by upgrading sewage infrastructures, which reduced viral loads in sewage. However, it is difficult to measure the significance of these improvements, as there are no regulations in place which stipulate the permissible limits for viruses. In most developing countries, including South Africa, there is a lack of effective management plans for virus monitoring in shellfish harvesting areas. The findings of this study indicated a need for extensive research on the origin of viruses, their interactions with other organisms within the marine ecosystem, the quantification of viruses within the Saldanha Bay harbour, and the development of virus management plans which currently are non-existent.

Keywords: shellfish; production areas; norovirus; hepatitis A; enteric viruses

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1. Introduction

The shellfish farming industry has seen exponential growth worldwide, providing an alternative source of protein needed for the growing world population [1,2]. Shellfish farming is conducted in rivers, estuaries, and open seas. In open seas, the ideal location is a sheltered embayment, often surrounded by residential and industrial areas. However, the challenge is the protection of shellfish farms or production areas from contamination [3]. Production areas are subjected to the discharge of treated and untreated sewage, which may be loaded with bacteria and viruses, as well as wastewater disposal from industries nearby, which may be loaded with chemicals and heavy metals [4–6]. Enteric viruses are widely spread in soil, water, and food. Viruses are also excreted in large quantities in the faeces of infected individuals (up to 10^{11} viral particles per gram of stool) [7] and are persistent in the environments where they are found [8]. Some of the enteric viruses of concern include norovirus Genogroup I and Genogroup II (NoV GI and GII); hepatitis A (HAV); rotavirus (RV), astrovirus (AsV); sapovirus (SaV), adenovirus (AdV), aichivirus (AiV), and Hepatitis E (HEV). The SaV, AiV, and HEV are regarded as emerging viruses [9,10]. Norovirus (NoV) is regarded as the most common cause of acute and nonbacterial gastroenteritis in humans and is implicated in most shellfish-borne viral outbreaks [11]. Furthermore, NoV is reported as the major causative agent in foodborne outbreaks in European countries after *Salmonella* bacteria. It was also associated with 457 outbreaks in 2019 in Europe [12], with oysters being the most implicated bivalve molluscs in foodborne outbreaks [13–16]. Hepatitis A (HAV) has also been reported as a cause of foodborne diseases [17], and a common cause of acute hepatitis infections worldwide with mild illnesses [18]. It is transmitted through the faecal-oral route from person to person or through the consumption of contaminated food or water. The biggest outbreak of HAV was in Shanghai in China in 1988, which was attributed to the consumption of raw clams [18]. Improved hygiene conditions and the introduction of the Hepatitis A vaccine caused a decline in cases until recently, in 2020 when an outbreak occurred in Yantai, which also implicated the consumption of contaminated shellfish. Other foods such as frozen berries have been implicated in an outbreak of HAV in Italy in 2013–2014 [19]. The Hepatitis E virus is a major cause of acute hepatitis in humans. Approximately 17 outbreaks have been reported in Africa annually since 1979 resulting in 650 deaths [20]. Pregnant women are at an increased risk of developing complications with HEV infection that could lead to fulminant hepatic failure [21].

Bivalve molluscs, including oysters and mussels, feed on suspended materials in their growing waters. They filter large quantities of water, subsequently accumulating and retaining contaminants available that are bound to the suspended materials [10]. Shellfish, apart from being a good source of protein and rich in micronutrients, play an important role in the marine environment as they purify water, thereby reducing eutrophication [22]. The nature of filter feeding is a public health concern as contaminants such as viruses can pose a health threat to shellfish consumers. Moreover, disease outbreaks where shellfish contaminated with enteric viruses are consumed are exacerbated by the norm of eating shellfish raw or partially cooked [23–25].

Sources of contaminants including sewage outfall, illegal wastewater discharge, stormwater discharge, heavy rainfall, agricultural runoffs, overboard disposal of faeces from boats, river flows, informal settlement dwellers, and natural disasters such as hurricanes and flooding increase the risk of contamination of shellfish growing areas [26–29]. Even though the available literature is mainly from other parts of the world, 17 studies were conducted on enteric viruses in shellfish over the past two decades in Africa [30]. In South Africa, studies were conducted on the contamination of rivers by enteric viruses [31–34]. Only a few studies are available on the contamination of shellfish by viruses and none so far explored virus contamination in Saldanha Bay [35]. Contaminants affecting Saldanha Bay shellfish farms are primarily from port operations (export of metal ores), ships traffic, ballast water discharge, oil spills, municipal sewage discharge, industrial effluent (brine, cooling water discharges, fish factory effluent), and stormwater discharge which may contain enteric viruses [36].

Impact of Enteric Virus-Contaminated Shellfish on Public Health

Norovirus has been implicated in 14–23% of global infections due to the consumption of contaminated shellfish. It is also responsible for 125 million foodborne illnesses and 35,000 deaths in a year [23]. Norovirus has six genogroups (GI–GVI), with genogroups I, II, and IV associated with human gastroenteritis infections. In the United Kingdom (UK), approximately 74,000 NoV cases due to the consumption of contaminated foods and 11,800 due to the consumption of contaminated oysters are reported annually [37]. Clinical symptoms include headache, fever, diarrhoea, abdominal cramps, and nausea.

Clinical symptoms related to HAV infections include jaundice, diarrhoea, abdominal pain, fever, malaise, and loss of appetite, with 1.4 million cases reported globally per annum [38]. It can also cause acute liver failure which may be fatal [39]. Studies conducted on HAV-contaminated foodstuffs have only contributed to 2–7% of all the food-related outbreaks worldwide, and are also reported as less common in bivalve molluscs compared to NoV [39,40]. Hepatitis E is receiving attention in food contamination as it affects 20 million people per annum with 56 600 deaths [41]. It is regarded as an emerging zoonotic foodborne threat [42]. Shellfish consumption is implicated in transmitting HEV in Asian countries such as China, Japan, Korea, and Thailand. In Vietnam, it has been detected in shellfish samples [40]. A few cases have also been reported in European countries, as well as the Netherlands, Spain, and the UK [9,40,41]. In Italy, HEV has not been detected in shellfish-approved harvesting areas [40]. In the African continent, HEV is a waterborne disease that is transmitted through faecal contamination of water and poor sanitation and hygiene. The lack of specific HEV surveillance in most African countries makes it difficult to monitor trends in disease incidence and identify outbreaks [21,43,44].

Aichivirus was reported in 1989 in Japan as the cause of oyster-associated nonbacterial gastroenteritis [45]. Sapovirus was first detected in an outbreak which occurred at an orphanage in Japan in 1977 and was detected in 3 out of 11 outbreaks in Japan which occurred between 2002 and 2006, due to the consumption of contaminated oysters [46,47]. Outbreaks are also common among children [47]. Rotavirus causes acute diarrhoea in children under 5 years of age, with clinical symptoms including diarrhoea, anorexia, dehydration, and occasional vomiting [17]. Clinical symptoms relating to Astrovirus infections include occasional vomiting, fever, abdominal pain, and anorexia. It has been detected in mussels and oysters, even though fewer outbreaks have been reported [48]. Rotavirus is one of the main causes of childhood diarrhoea worldwide. It has not been linked to gastroenteritis outbreaks related to seafood; neither has adenovirus [49]. Table 1 shows some of the documented foodborne disease outbreaks due to viral infections.

Table 1. Enteric viruses associated with shellfish disease outbreaks.

Enteric Virus	Country and Year	Bivalve Mollusc	References
Norovirus (GI and GII)	France, 2012 Canada, 2016 US, 2009–2014 South Korea, 2013 France, 2019	Oyster Oyster Oyster Oyster Oyster	[50] [16] [15] [51] [52]
Hepatitis A	Hawaii, 2016 China, 1988 China, 2020 Italy, 1997–2004 Australia	Scallops Clams Oyster Raw shellfish Oysters	[53] [18] [18] [54] [17]
Aichivirus	Japan, 1989	Oyster	[13]
Sapovirus	Japan, 1977	Oyster	[46]
Astrovirus, adenovirus, Rotavirus		The rapid increase in cases but not frequently implicated in outbreaks occurrence [9,48]	

Apart from the contaminants mentioned above, there are currently contaminants described as emerging contaminants (pharmaceutical products, personal care products, antibiotics, surfactants, artificial sweeteners, flame retardants, cleaning solvents, sun protection products, etc.), including microplastics. Their presence in the marine ecosystem is a concern for the health of marine organisms. They are aggressive in nature, have toxic effects and the ability to bioaccumulate, and are not effectively removed from sewage by traditional wastewater treatment methods [55]. Microplastics may act as vectors for the spread of antimicrobial-resistant genes, harmful microorganisms, and as a microcosm for gene exchange between bacteria [56–58].

The microbiological monitoring programme in Saldanha Bay is well-established in the monitoring of bacterial contamination, but lacking in virus contamination monitoring. This review aims to gather epidemiological data available on virus contamination at shellfish harvesting areas. The existing data could assist with relevant information for policy-makers to consider when developing policies and strategies for managing virus contamination in Saldanha Bay.

2. Materials and Methods

For this desktop review, all literature on virus contamination in shellfish harvesting areas worldwide was included. The literature search was conducted using online electronic databases such as Science Direct, Scopus, and Google Scholar with a timeframe of 2012 and 2022 to ensure that the latest information was included. However, there were no timeframe restrictions on the introduction and discussion sections. The Boolean logical connectors ('AND' and 'OR') and truncation were applied in the search strategy. The search terms were mussels and oysters AND hepatitis A and "norovirus GI and GII" AND production areas OR shellfish farms OR growing waters AND sources. The following inclusion and exclusion criteria were used: the original articles written in English from peer-reviewed journals and the prescribed timeframes were included. Unpublished papers, theses, non-peer-reviewed articles, articles on mussels and oysters from wholesale and retail markets, food processing, post-harvest treatments, book chapters, and abstracts were excluded. The exclusion and inclusion criteria were strictly followed to reduce the risk of biases. Two reviewers worked together to screen records and retrieve reports. A report was retrieved from the Scopus database. Reports were not available for retrieval from Google Scholar and Science Direct. Records screened from Google Scholar and Science Direct that met the inclusion criteria were saved in the Google Scholar library of one of the reviewers. The screening, evaluation, and identification of records for eligibility were conducted following the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) flow diagram (Figure 1) [59].

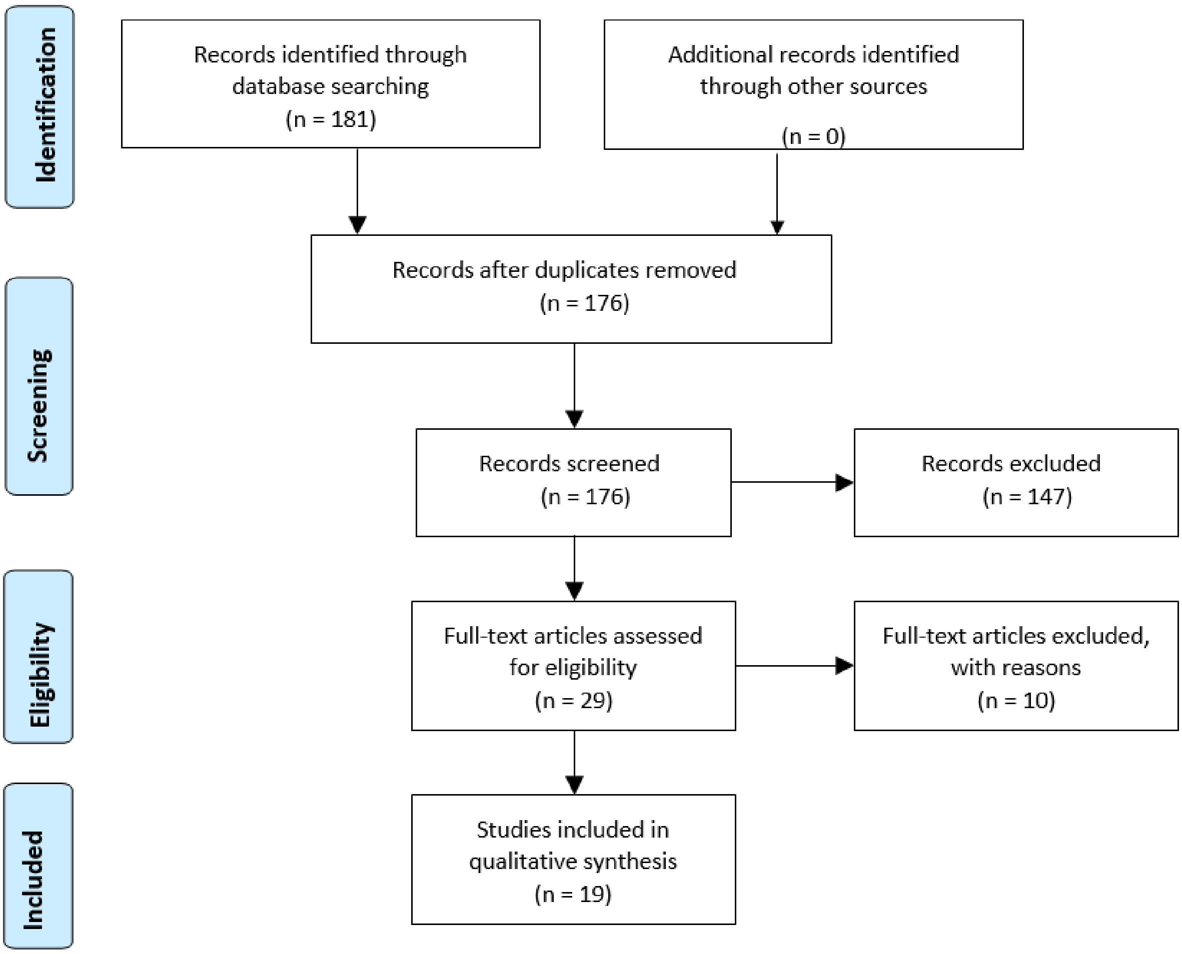

Figure 1. PRISMA methodology of literature search (available from: http://www.prisma-statement.org, accessed on 6 September 2022).

3. Results

A total of 181 records were identified through a database search. After screening the records and looking at titles, abstracts, and duplicates, 147 records were excluded. Full texts of the remaining 29 were scrutinised for eligibility and 10 records were excluded. Nineteen records were retained for qualitative synthesis (Figure 1).

Table 2 summarises the findings and recommendations of the studies that were included in this review. Most of the studies implicated sewage discharge in shellfish growing areas as the source of enteric virus contamination. Therefore, they recommended the development of effective management plans for shellfish harvesting areas, and the development of virus compliance limits as well as virus indicator species, since the use of *E. coli* has proved to be ineffective in detecting viral contaminants. Table 2 also represents the literature available on enteric viruses' contamination in shellfish harvesting areas and the studies conducted according to the search keywords used per country. The data search was from 2012 until September 2022, the studies conducted per country are as follows: Britain (1); Italy (6); Australia (1); England and Wales (1); Montenegro Coast (1); Brazil (3); France (1); Argentina (1); Spain (1); Poland (1); Korea (1); and Morocco (1). These studies included Hepatitis A, norovirus, and other emerging viruses, with a focus on contamination in harvesting areas. Most of the studies conducted were on oyster contamination with the most implicated virus being norovirus.

Table 2. Summary of studies included in the review that met all the criteria specified.

Study Area	Aim of the Study	Findings	Recommendations	References
Poole Harbour, Britain	(1) To determine the impact of geographical and temporal changes on *E. coli* and norovirus in mussels. (2) Influence of environmental factors.	(1) High concentrations of NoV on sampling sites close to the sewage discharge point. (2) Higher concentrations of *E. coli* in mussels than in seawater.	Geographical and temporal variations must be considered in harvest area monitoring programmes and most importantly incorporated into food safety regulations and harvest area management plans.	[11]
Syracuse, Italy	Assessment of enteric viruses including HAV and NoV in bivalve molluscs.	Detection of enteric viruses indicates they are widely distributed in aquatic environments.	(1) Development of strategies and methodologies to assess public health risks. (2) Systemic controls for viral pathogens to protect consumers. (3) An integrated surveillance system reporting food safety, environmental exposure, and clinical cases.	[8]
Gulf of Pozzuoli, Italy	Determine existence of a relationship between viral and chemical contamination.	Oysters demonstrated a possible link between chemical pollutants and the bioaccumulation of multiple enteric viruses.	Efficient monitoring of harvest areas to determine a correlation between environmental pollutants and foodborne viruses.	[10]

Table 2. *Cont.*

Study Area	Aim of the Study	Findings	Recommendations	References
Sardinian shellfish farms, Italy	(1) Detection of *E. coli,* HAV and NoV in shellfish samples. (2) Assessment of possible relationships between pathogens and seasonality.	Norovirus was prevalent in all areas during the winter season.	(1) Stringent shellfish monitoring programmes. (2) Inclusion of environmental parameters. (3) Improved monitoring plans could lead to better management of shellfish harvest areas.	[60]
Baltic Sea, Poland	Evaluate NoV and HAV occurrence in wild Baltic mussels and possible inclusion as indicator species for viruses.	Underreporting of viruses' occurrence in wild shellfish could limit insight into the role they play in environmental viral transmission.	The development of viral indicators such as *E. coli* is not effective in the prediction of viral pollution.	[61]
Australia, New South Wales, Tasmania and South Australia	Assess the occurrence of NoV and *E. coli* in Pacific oysters and Sydney rock oysters.	The human population around the shellfish growing areas is lower in Australia compared to other countries.	An increase in viral contaminations calls for control measures specific to virus pollution in shellfish-growing areas.	[7]
Commercial harvesting areas- coast of England and Wales	Determine the possible predictor variables for NoV in oysters.	Heavy rainfall was implicated in high concentrations of *E. coli* levels.	Viruses-specific control measures are required for monitoring harvesting areas. Improvement of sewage infrastructure and improvement of risk management measures.	[62]
Campania region, Italy	To establish a relationship between environmental parameters and viral contamination.	The presence of chemical contaminants influenced viruses' bioavailability.	Integration of microbiological and chemical monitoring programmes as an effective warning system.	[63]
Gulf of Naples, Italy	Evaluate the effects of the different enteric viruses within bivalve molluscs.	Confirmed circulation of multiple enteric viruses in bivalves.	Consumer awareness campaigns on the importance of cooking seafood thoroughly.	[63]
Montenegro Coast	To determine the distribution rate of NoV in mussels along the coast.	Seasonality and the human population contribute to the prevalence and spread of viruses.	(1) Improvement of shellfish monitoring programmes. (2) Development of virus-specific criteria.	[64]

Table 2. *Cont.*

Study Area	Aim of the Study	Findings	Recommendations	References
Mangrove Estuary, Brazil	Quantify enteric pathogenic viruses.	(1) High concentrations of HAV, NoV and AdV were detected during winter months in water, mussels, and oyster samples. (2) Estuary should be classified as a prohibited zone for bivalve harvesting for human consumption.	Improvement in shellfish monitoring programmes.	[49]
Atlantic Coast Lagoon, France	NoV contamination and gastroenteritis outbreaks.	Seasonality and high prevalence of NoV in oysters.	(1) Prevention of contamination. (2) Development and implementation of an outbreak alert system.	[65]
Production in Sicily, Italy	To develop a routine monitoring plan for enteric viruses.	Prevalence of enteric virus.	Development of a monitoring system for viruses, using data from epidemiological studies and existing molecular methods.	[66]
Southern Coast of Buenos Aires Province, Argentina	To determine the presence of NoV and RvA in oysters.	Detected NoV in RvA in samples and resistance to heat treatment.	Understanding viruses' circulation to improve existing surveillance plans.	[67]
Galicia, Spain	Compile a database on the prevalence of enteric viruses in shellfish.	(1) Harvest areas affected by close proximity to pollutants discharge points and dilution factors. (2) Role of bivalves as a vector of zoonotic diseases.	A better understanding of emerging enteric viruses' behaviour and pathogenicity.	[42]
Jinhae Bay, Korea	Investigate the contamination status of the oyster growing area by NoV and the circulation of NoV genotypes.	NoV GII strains are the most prevalent in oysters and elimination can be difficult.	(1) No commercial harvesting in polluted areas. (2) Prevent faecal contamination in production areas.	[68]
Florianópolis, on the coast of Santa Catarina, Brazil	To perform a thorough diagnosis of the shellfish growing areas.	(1) Contamination by various pathogens due to sewage discharge. (2) Complexities of microbiological and chemical compound contaminants.	Control measures are necessary to ensure the safety of produce.	[69]
Lagunar complex Cananéia, Brazil	Analysed the presence of Astrovirus and NoV in mussels and oysters.	Mussels and oysters tested positive for the studied viruses.	Mapping out the pollution sources, using the findings to develop risk assessment and control measures of pathogen contamination.	[48]

Table 2. *Cont.*

Study Area	Aim of the Study	Findings	Recommendations	References
Oualidia Lagoon, Morocco	Evaluate NoV frequency in bivalve shellfish harvested at Oualidia lagoon.	Risk of contamination in oysters.	Importance of implementing a national survey plan and sanitary control for the viral risk, including NoV in bivalve molluscs.	[70]

4. Discussion

Contamination of bivalve molluscs with viruses is a global concern. Vulnerable people such as the elderly and immunocompromised individuals die when foodborne outbreaks occur [23]. According to Table 2, only one study was conducted on the African continent. Urgent interventions are needed for the continent to develop food safety in the shellfish industry to the same level as other developed and developing countries. Detection of HAV and NoV indicates that these agents are widely distributed in aquatic environments [71,72]. This correlates with global trends where sewage is discharged along the coastal areas, including African countries and South Africa in particular. The findings and recommendations from the nineteen studies listed in Table 2 could be a starting point for the development of management plans for virus detection and monitoring in Saldanha Bay. The summary of findings and recommendations according to Table 2 is as follows:

High concentrations of NoV at harvesting areas or sampling sites close to the sewage discharge point were mentioned by most of the studies. Disposal of sewage whether treated or untreated is a major challenge facing the shellfish industry globally [23,26,37,73–76]. Sewage discharge points near shellfish harvesting areas give rise to the challenge of eliminating viruses by bivalve molluscs. Pouillot et al. [76] demonstrated in their study how oysters bioaccumulated viral particles in high concentrations within a short period. They also added that through the bioaccumulation process, virus concentrations in oyster tissues exceeded the virus concentrations in the water. Similarly, Sharp et al. [75] observed high concentrations of NoV in mussels within 3 h of exposure to water contaminated with treated and untreated sewage. Souza et al. [77] added that viral particles may be 100 times more concentrated in bivalve molluscs' organs than in contaminated seawater. To prevent contamination of commercially harvested bivalves, the United States Food and Drug Administration (USFDA) determined a prohibition zone, where bivalves may not be harvested for commercial purposes, and decided on the dilution criteria of 1000 parts of receiving waters to every part of effluent (1000:1) [78]. These were determined through comparisons of studies such as USFDA hydrographic dye dispersion and numerical hydrodynamic models to track the discharge of wastewater. The 1000:1 dilution criterion is equated to waters within a distance of 3.77 km from the sewage outfall [79]. Schaeffer et al. [80] also agree with having a buffer zone whereby shellfish harvesting is prohibited if contamination cannot be prevented.

Chemical contaminants from industrial activities and runoffs from land also pose a challenge and a public health risk. The risk for consumers differs depending on the chemical compounds formed by different chemicals. For example, Arsenic (As) in its inorganic form may alter tumour-suppressing genes and has been classified by the International Agency for Research on Cancer (IARC) as cancer-causing in humans [81]. Fiorito et al. [59] in their studies observed a correlation between chemical pollutants and viral contaminants in mussels. The mussels that tested positive for viral presence exhibited higher levels of chemical pollutants than the mussels that tested negative for viral contaminants. The higher the exposure to chemical agents, the weaker the immune system and thus the higher the uptake of microbial agents [82]. The effects of having both biological and chemical contaminants need to be explored further to ascertain a possible link between chemical pollutants and the bioaccumulation of multiple enteric viruses in bivalve molluscs [59]. Adding to the burden of chemical contaminants are microplastics, which are considered emerging pollutants. Owing to their small size, they can be mistaken for food by bivalves. Some studies demonstrated that mussels and oysters ingest microplastic particles from the surrounding seawater [83]. Although the potential for human viruses to attach to microplastics and to persist in the plastisphere is unclear [83], Moresco et al. [58] indicated that biofilm on surfaces of plastics could provide a platform for viral attachment. Yamada et al. [84] agreed with the suggestion that microplastics could be potential adsorbents for viruses. However, they added that more research is needed on the influence viruses have when attached to biotic and abiotic particles in marine ecology, as well as the extent to which these attached viruses are infective to their hosts. On the other hand, it is well established that microplastics can provide a habitat for the colonization and enrichment of Vibrio species and vectors of pathogenic bacteria including *Pseudomonas* and *Acinetobacter* [85]. The danger lies in the possibility of microplastics being a vehicle for the spread of infection in aquaculture which could have a detrimental economic impact [56].

Bivalve production sites are mostly situated along the coastal areas [27,86,87], where possible exposure to sewage contaminated with human enteric viruses is high. Bivalves act as zoonotic disease vectors through the bioaccumulation process when filtering the water in their growing areas. The concentration and retention of enteric viruses for long periods pose a public health threat as bivalves are commonly eaten raw or partially cooked, particularly oysters [37]. Coastal areas are becoming more attractive for residential developments and tourism (which is important for the coastal economy) as some are secluded and bring about peace and quality of life away from densely populated suburban metropolitan areas [88]. Such developments bring an increase in activities such as boating, snorkelling, fishing, and many more activities which may introduce pollution into the ocean near the developments [89]. To meet the demands of the human population increase, agricultural lands are converted into residential and industrial developments, leading to altered water quantities and quality, as well as altered sediment which ultimately lands in the ocean, increasing faecal microbial loads, and nutrients [4]. El Mahrad et al. [90] reported and described changes that are brought about by human influx in a coastal city in Morocco, including alteration of sedimentary forms especially the dunes on the east side of the lagoon. Furthermore, changes in ocean chemistry may cause ocean acidification, changes in precipitation, a rise in sea levels, and changes in seawater pH [91]. Increased inputs of nutrients could trigger harmful algal blooms [92].

A summary of the recommendations is as follows:

Geographical and temporal variations must be considered in monitoring programmes of harvesting areas and incorporated into regulations or harvesting area management plans. The environmental factors within the harvesting areas play a role in microbial pollutants' prevalence [60]. Strubbia et al. [11] observed high microbiological contamination at a site that was receiving large amounts of sewage discharge and concluded that such events must be taken into consideration for monitoring harvesting areas. Microbial pollutants are not the only aspect affected by geographical and temporal variation, marine biotoxins also show similar trends. Goya et al. [93] identified temporal variability with paralytic shellfish poisoning toxins which were higher in summer months, lower in winter, and lowest in autumn. According to Wu et al. [94] regional and seasonal differences were observed, where some biotoxins bloomed during the upwelling season and some during the downwelling season. Spatial and temporal variability could also be due to coastal natural processes and local changes in environmental conditions [95].

There seems to be a consensus about the lack of effective management plans or strategies in shellfish harvesting areas [10,11,42,56,64]. Some researchers also highlighted the need to have an integrated surveillance system that will enable simultaneous reporting on environmental exposure and clinical cases to facilitate tracking and correlation of occurrences of clinical cases with environmental factors in harvesting areas [8]. La Rosa et al. [43] agreed with the concept of an integrated surveillance system and added that it could be useful to monitor changes in viral patterns and could offer a warning of contamination in advance. Some researchers also recommended the inclusion of environmental parameters in shellfish management plans for the correlation between meteorological events and the prevalence of viruses. Furthermore, the development of viral indicators [96] is required, as *E. coli* is not effective in the prediction of viral pollution as it has lower environmental resistance than viral pathogens [11]. Sharp et al. [75] demonstrated in their study how oysters accumulated *E. coli* and norovirus in their bodies and how both microorganisms responded to depuration, with *E. coli* being successfully purged from the shellfish tissues within 72 h but failed to remove norovirus from the shellfish tissues. Several studies proposed the use of bacteriophages as indicator species for viral contamination. Others proposed the use of norovirus as an indicator species [7,26,64,75,97]. The traditional way of eating bivalve molluscs, i.e., raw or undercooked, appears to be a health risk and consumer awareness is necessary. Consumers are perceived to be aware of chemical hazards in food as they cause long-term adverse effects including cancer and are less concerned about microbial hazards [98]. Ricardo et al. [99] added that it is important to precisely know the bivalve origin and the sources of pollutants considering their sedentary lifestyle and feeding behaviour. They bioaccumulate pollutants, which is exacerbated by how they are eaten (raw or undercooked), leading to the risk of transmission of infections to humans. More studies on foodborne outbreaks associated with shellfish consumption will increase consumer awareness [100]. Crovato et al. [101] evaluated studies that conducted research on shellfish consumption and reported that consumers were confused about the risks and benefits of bivalve molluscs. They concluded that accurate information is necessary for helping consumers to make informed choices. In addition, Fiorito et al. [63] highlighted the importance of awareness campaigns to inform consumers of the thorough cooking of seafood. This remains a challenge as people prefer eating oysters raw and mussels lightly cooked [102].

Evaluation of sources of pollutants is the first step that may lead to effective management of shellfish harvesting areas. Knowing what pollutants are present, where they come from, and their composition will enable policymakers to develop management plans and monitoring programmes accordingly [48]. For example, Mok et al. [102] evaluated the bacteriological seawater quality and oyster quality from a coastal area in Japan, where they conducted a sanitary survey to analyse all the possible sources of pollutants. The study concluded that faecal coliform levels were high after heavy rainfall events compared to other sampling occasions. Therefore, it was reported that oysters are safe to be consumed raw during dry seasons based on their bacterial water quality. Chinnadurai et al. [103] similarly evaluated seasonal occurrences of faecal coliforms and found elevated levels during monsoon periods, and therefore suggested that authorities develop sanitary control in line with international standards, as no microbiological standards existed. The prevalence of viruses is influenced by seasonality. Several studies reported high concentrations of NoV during the winter season when heavy rainfall occurred [65,74,76,104–107]. Lower concentrations were measured in summer months with low rainfall, which is suggested to be due to the inactivation of viruses by sunlight and viral clearance because of the high metabolic rate in summer [12]. A sanitary survey process identifies and evaluates all environmental factors and actual and potential sources of pollution that could harm the water quality of shellfish growing waters [103].

The National Shellfish Sanitation Program [78] outlines what a sanitary survey must entail which includes conducting a shoreline survey, and a survey of the microbiological quality of the water. In addition, an evaluation of the effect of any meteorological, hydrodynamics, and geographic characteristics on the growing areas will assist in determining the appropriate growing areas' classification. Once a sanitary survey exists, it must be updated or reevaluated every three years. An annual review based on meteorological and hydrodynamics should also be performed to ensure that conditions are unchanged. Regulations have been developed internationally, regionally, and locally to specify acceptable levels of bacterial pathogens in shellfish tissues or in water where shellfish are grown. This has led to the classification of production areas for shellfish harvest fit for human consumption [108].

Standards are available for the detection of HAV and NoV in some food groups, which would eventually lead to the establishment of regulations where set compliance limits for enteric viruses in shellfish are specified [109].

Emerging viruses must also be prioritised due to the rapidly increasing number of cases associated with them [71]. As mentioned, the presence of viruses in food is a global concern, with viruses such as norovirus and Hepatitis A causing foodborne outbreaks [9]. Further studies are needed on the occurrence, behaviour, and genotype distribution of emerging enteric viruses in the environment, their epidemiology, temporal and geographical distribution, environmental stability, and potential health risks to humans [64,110].

Effective risk management strategies need to focus on the prevention of contamination [107]. The European Food Safety Authority (EFSA) recommended that contamination should be prevented in the first instance, which might be achieved by ensuring viral treatment of sewage or growing oysters sufficiently distant from sewage outflows (European Food Safety Authority, 2019) [111]. Shin et al. [68] are of the same view that the most effective control measure is to prevent faecal contamination in oyster production areas or to restrict commercial harvesting from contaminated production areas. Campos et al. [64] emphasised that if this recommendation was to be successful or effective, it would require a good understanding of the environmental factors influencing the movement of NoV and other enteric viruses within the hydrological catchments and integration of microbiological and chemical monitoring programmes for effective warning systems. Written management plans are required for each shellfish growing area. Detailed reports on characteristics of effluent discharged near shellfish growing areas, dilution factors depending on the classification of growing areas, determining the distance from the pollution sources to the growing areas, and the impact of each source on the growing area should be compiled [78]. Several studies have shown that world population growth and urban developments have a detrimental impact on the microbiological quality of freshwater ecosystems and marine ecosystems [4,62,97,112,113]. Webber et al. [114] in their study detected the presence of NoV, AdV, and RT in shellfish farms and found that the treatment of sewage did not provide effective removal or elimination of pollutants. Garbossa et al. [112] also reported in their study that shellfish farms are at risk of being contaminated with enteric viruses which are transported to the farms through sewage discharge and indicated that the current wastewater treatment plants are not designed to effectively remove enteric viruses. Trottet et al. [28] and Hassard et al. [23] recommended upgrades of existing wastewater treatment plants, effluent pipes, or shellfish bed relocation based on principles of dilution factors' zoning. Campos et al. [115] tested the effectiveness of faecal coliform load reduction after the improvement of a sewage treatment plant's infrastructure and observed a reduction in *E. coli* concentrations with the greatest reduction identified at a site more distant from sewage discharges.

The available literature is mostly from developed countries and some developing countries (Table 2). The available literature on the African continent shows that only 17 studies were conducted in the past two decades in detecting enteric viruses in Africa [30]. In Saldanha Bay, on the West Coast of South Africa, where both mussels (*Mylitus galloprovincialis*) and oysters (*Crassostrea gigas*) are farmed, monitoring of bacteriological contamination is conducted, while monitoring of enteric viruses is lacking. The findings of this review highlight the importance of monitoring enteric viruses for the safety of public health, and therefore, may serve as a baseline for the development of a management plan for enteric viruses in Saldanha Bay, Western Cape, South Africa.

5. Conclusions

This review provides information on the global prevalence of enteric viruses in studies conducted between 2012 and 2022 in shellfish production areas. The findings confirm that shellfish contamination happens in harvesting areas that are subjected to the discharge of treated and untreated sewage continuously or intermittently. Several studies are of the view that the effective control measure for viral contamination is to harvest shellfish in areas that are not faecally contaminated and encourage the development of effective viral management plans for shellfish harvest areas. Quantification of the virus community in Saldanha Bay Harbour is crucial as well as quantification of existing pollutants and emerging pollutants to develop comprehensive strategies in the management of viruses as contaminants for bivalve molluscs. This study will serve as a baseline for the shellfish industry in South Africa to consider monitoring viruses and developing management plans for viruses. Before the development of management plans for viruses, extensive research is needed in understanding viruses' origins, the influence brought by interaction with other organisms within the marine ecosystem, and the potential risks to consumers.

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