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Impact of sewer overflow on public health: A comprehensive scientometric analysis and systematic review

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Abstract

Sewer overflow (SO), which has attracted global attention, poses serious threat to public health and ecosystem. SO impacts public health via consumption of contaminated drinking water, aerosolization of pathogens, food-chain transmission, and direct contact with fecally-polluted rivers and beach sediments during recreation. However, no study has attempted to map the linkage between SO and public health including Covid-19 using scientometric analysis and systematic review of literature. Results showed that only few countries were actively involved in SO research in relation to public health. Furthermore, there are renewed calls to scale up environmental surveillance to safeguard public health. To safeguard public health, it is important for public health authorities to optimize water and wastewater treatment plants and improve building ventilation and plumbing systems to minimize pathogen transmission within buildings and transportation systems. In addition, health authorities should formulate appropriate policies that can enhance environmental surveillance and facilitate real-time monitoring of sewer overflow. Increased public awareness on strict personal hygiene and point-of-use-water-treatment such as boiling drinking water will go a long way to safeguard public health. Ecotoxicological studies and health risk assessment of exposure to pathogens via different transmission routes is also required to appropriately inform the use of lockdowns, minimize their socio-economic impact and guide evidence-based welfare/social policy interventions. Soft infrastructures, optimized sewer maintenance and prescreening of sewer overflow are recommended to reduce stormwater burden on wastewater treatment plant, curtail pathogen transmission and marine plastic pollution. Comprehensive, integrated surveillance and global collaborative efforts are important to curtail on-going Covid-19 pandemic and improve resilience against future pandemics.

Keywords: Sewer overflow; Public health; Scientometric; Systematic review; Covid-19

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1. Introduction

Sewer overflow (SO) is the release of raw or poorly treated wastewater and fecal-derived pathogens into the environment, which could be land, water bodies (e.g. sea, river, swimming pool, etc.), groundwater or air. SO is a threat to the global ecosystem because it pollutes air, groundwater and surface waters (Aad et al., 2010). Therefore, SO control is highly important in megacities due to their ubiquitous impervious surfaces that have disrupted natural hydrology (Eaton, 2018). Consequently, there is an increase in stormwater runoff. Furthermore, many cities discharge pathogen-laden wastewater into water bodies, which can lead to an outbreak of epidemics. Previous outbreaks have been linked to the transmission of food-chain pathogens via pathogen-laden wastewater, person-to-person transmission, and close contact with infected animals (Al-Omari et al., 2019; Caplin et al., 2008; Mackay and Arden, 2015).

Furthermore, recent studies have reported pathogen transmission due to aerolized pathogens and leakages in plumbing systems in hospitals and high-rise buildings (Ding et al., 2021; Gormley et al., 2020; Kotay et al., 2019; Snitkin, 2019; WHO, 2020). Another study also reported sewer overflow into groundwater as a result of faulty sewer pipe joints, sewer leakage, sewer pipe blockage, and poor network repair activities (Yang et al., 2021a). Evidences have also emerged on potential Covid-19 transmission via SO of untreated sewage or wastewater (Han and He, 2021). The global cost of the Covid-19 pandemic is estimated to be US$ 16 trillion (Cutler & Summers, 2020) and has caused 2,462,911 deaths globally (WHO, 2021). This ongoing pandemic is capable of reversing previous developmental achievements in poverty alleviation and public health … and hence, global concerted efforts are required to curtail its socio-economic impact. Therefore, it is necessary to prevent SO to curtail the spread of Covid-19. This is important because wastewater and sewage are the final environmental reservoirs of most pathogens (Bogler et al., 2020).

Stormwater runoff is rainfall that flows over the ground surface including roads, streets, developed and undeveloped lands, rooftops and other paved surfaces. Conventionally, stormwater runoffs are collected in drainage system (or storm sewers) and transported to nearby water bodies while sanitary sewer system transports sewage, domestic and industrial wastewater to the wastewater treatment plant. However, during the 19/20th century, in order to temporarily curb urban flooding in cities, and to reduce construction cost, combined sewer systems were launched in many cities globally, without taking into consideration of their long-term effects (Tibbetts, 2005). The combined sewer systems transported both stormwater runoff and wastewater to the wastewater treatment plants (WWTP). With increased climate change in cities and increased impervious surfaces in urban areas to meet infrastructural developments, the volume of stormwater runoff increased significantly such that the combined volume of stormwater runoff and wastewater exceeds the capacity of the wastewater treatment plant. This situation results in emergency release of the stormwater runoff and untreated wastewater into receiving water bodies, a term called sewer overflow (SO). The sewer overflow results in pollution of the impacted water bodies such as rivers and streams, serious degradation of their water quality and constitute environmental and public health risks (Borchardt and Statzner, 1990; Kim et al., 2007; Mueller and Anderson, 1979; Tavakol-Davani et al., 2016).

Various studies have linked non-point source pollution caused by stormwater runoff to chronic and acute illnesses from exposure through drinking water, seafood and contact recreation (Gaffield et al.; Goldstein et al., 1996; Haile et al., 1996; Levin et al., 2002; Rose et al., 2001). And the greatest risks from waterborne pathogens were children, elderly, pregnant women and immunocompromised (Boulos, 2017). In addition, urban stormwater runoff is responsible for about 47% of pathogens in stormwater runoff while the remaining is supplied by combined stormwater drainage and sanitary sewer systems discharges which are disposed untreated into receiving water bodies when the stormwater runoff exceeds the WWTP capacity during rainfall (Gaffield et al., 2003). In addition, it is estimated that 1.8 million people globally are at risk of potential Covid-19 transmission if fecal contamination of drinking water sources by sewage and wastewater is not well managed (Bhowmick et al.).

Though no link between SO and Covid-19 pandemic has been established, recent studies reported that fecal aerosols transmission of Covid-19 via wastewater through building plumbings is possible and lower than person-to-person transmission via respiratory droplets/aerosols (Ahmed et al., 2021; Gormley et al., 2020; Shi et al., 2021). Direct contact with and proximity to bioaerosols from CSO effluents have been linked to increased elevated risks of asthma, gastrointestinal illnesses and skin and soft tissue infections in children residing near SO sites (Brokamp et al.). Also, inadequate water and sanitation infrastructure for disposal and treatment of sewage also contributed to Covid-19 transmission (Eichelberger et al., 2021). SO have been linked to elevated fecal pathogen concentration and prevalence of antibiotic resistant bacteria in Germany (Stange and Tiehm, 2020). SO and runoff serve as environmental driving forces of particle-attached pathogens during storms with significant consequence to both ecosystem and public health (Jørgensen et al., 2018; Noyer et al., 2020). SOs and floods serve as potent threat to spread co-resistant and cross-resistant pathogens due to shifts in pathogen communities and this risk is expected to increase with current trend of increased climate change and urbanization (Noyer et al., 2020).

Previous studies on SO have mainly focused on monitoring, modelling and controlling SO. For instance, some previous reviews assessed the linkage between constructed wetlands and SO (Botturi et al., 2020; Rizzo et al., 2020; Tao et al., 2014). Other studies focused on quantitative detection of micro-organisms, quantitative microbial/public health risk assessment, pretreatment and disinfection of SO, removal of virus from wastewater, quantitative detection of micropollutants such as pharmaceuticals and industrial chemicals and measurement of impact on microbiological water quality (Chhetri et al., 2016; Eregno et al., 2016; Fong et al., 2010; Goulding et al., 2012; Ibrahim et al., 2021; Launay et al., 2016; Passerat et al., 2011) . Also, some studies focused on prediction and monitoring of SO, monitoring of frequency and duration of SO and sensor-based monitoring of freshwater bodies for public health advisory (Hofer et al., 2018; Morgan et al., 2017; Rome et al., 2021; Rosin et al., 2021). Some review studies focused on management of emerging wastewater-derived contaminants and wastewater flow, systematic review of stormwater runoff pollution control technologies, urban flood mitigation restoration of rivers affected by SO and remediation of surface waters using constructed wetlands (Peters and Zitomer, 2021; Petrie, 2021; Qi et al., 2021; Wang et al., 2021b; Zhao et al., 2021) . Limited studies have demonstrated the linkage between SO and public health.

Scientometric review is an effective approach for gaining comprehensive understanding of past, current and emerging research areas through visualization of research trends and progress, identification of multiple relationships among research clusters as well as research gaps for future research (Darko et al., 2019; Li et al., 2020; Martinez et al., 2019; Olawumi and Chan, 2018; Wang et al., 2020; Wuni et al., 2019; Zhao, 2017). Advantages of scientometric review include provision of evidence of impact of researches done, predicts future research directions based on identified research gaps, guides funding provision for identified impactful research at both local and international levels and provides opportunity for collaboration with productive research networks, institutions and countries (Chen et al., 2021a; Darko et al., 2019; Olawumi and Chan, 2018; Yao et al., 2014). While previous scientometric reviews focused on global health systems, coronaviruses, climate change, drinking water treatment technologies, and sustainability and sustainable development to mention a few (Gonzales et al., 2021; Li et al., 2020; Malik et al., 2021; Olawumi and Chan, 2018; Yao et al., 2014), no scientometric review has mapped the linkage between sewer overflow and public health.

On the other hand, systematic review is the comprehensive appraisal and synthesis of available and relevant evidence using reliable, objective and thorough standard research protocols to answer specific research question(s). Advantages of systematic reviews include provision of clear, balanced and impartial summary of findings in an understandable format to facilitate decision making, resolution of conflicts in literature andprovision of clear research agenda for grant/funding purposes. Previous systematic reviews focused on green infrastructure developments, stormwater management and challenges, public health policies, interventions and communities of practice and nature-based solutions to reduce impact of flooding on human health, improve socio-economic well-being and public health (Barbour et al., 2018; Hallingberg et al., 2018; Lal et al., 2018; Masters et al., 2017; Qiao et al., 2018; Sohn et al., 2019; Van den Bosch and Sang, 2017; Venkataramanan et al., 2020; Venkataramanan et al., 2019).

. Based on review of existing literature, it was observed that studies analysing and providing a comprehensive understanding of the research trend in SO and their linkage to public health are currently not available. To address these weaknesses and fill these research gaps, both scientometric and systematic literature reviews are undertaken in the current study. Therefore, the aim of this study is to establish linkage(s) between sewer overflow and public health using both scientometric analysis and systematic literaturereviews. The objectives of this study are to: (i) identify the most influential keywords, journals, scientists, and countries active in sewer overflow and public health research; (ii) reveal the methodological approaches utilized in the studies, their applications and study area; and (iii) highlight prominent and emerging research gaps based on in-depth systematic review of the existing literature. This study is significant because it reveals the link between sewer overflow and public health, as well as emerging research gaps to curtail the ongoing pandemic. Furthermore, this study serves as a consultation toolkit for effective policy making to safeguard public health and improve societal resilience to future pandemics.

2. Research Methodology

The review framework adopted in this study is shown in Figure 1. The review goals were identified and keyword search was conducted in the Scopus database using the phrase “impact of sewer overflow”. Filters, such as limiting the language of publication to English and subject area to English and Engineering, were applied. Thus, 43 relevant papers were identified.

Furthermore, forward and backward snowballing techniques were utilized to identify additional relevant papers to increase the total number of retrieved papers to 206. These papers were subjected to scientometric analysis with the aid of the VOSviewer software. Thereafter, a systematic review of the retrieved literature was done.

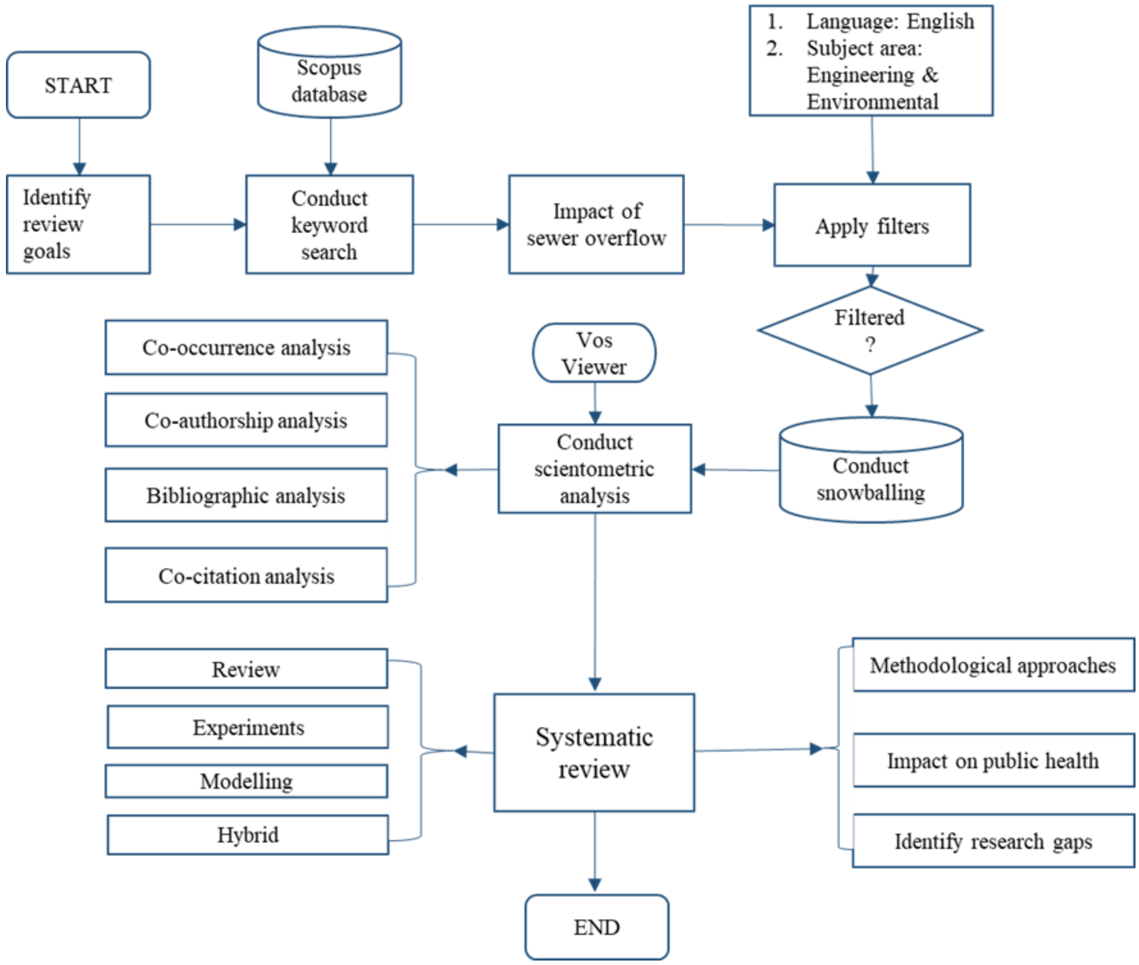


Figure 1. Review framework

3. Scientometric analysis

3.1 Keyword cluster analysis

Keyword cluster analysis identifies 295 keywords in SO research. Four keywords clusters are prominent in the keyword network map shown in Figure 2. Cluster 1 is displayed in red, cluster 2 in green, cluster 3 in blue, and cluster 4 in yellow. The keyword map illusrates the interrelationship between various keyword clusters. During extreme rainfalls in cities and urban areas, stormwater runoff and sewage are transported through the sewer network to wastewater treatment plants (WWTPs). The combined stormwater and sewage are rich in organic matter, sediments and micro-organisms, such as *E.coli* and fecal coliforms.

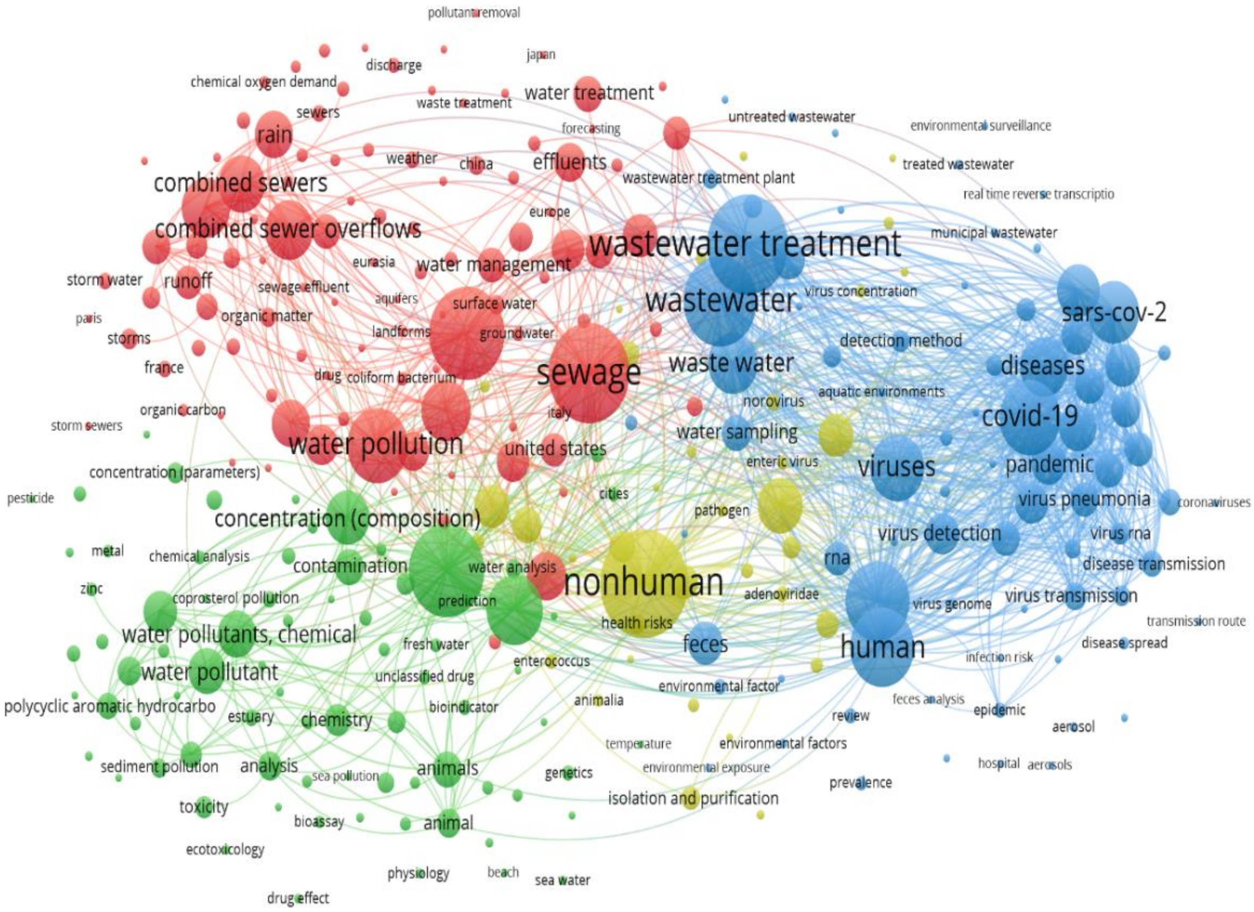


Figure 2. Co-occurrence of keywords network

Owing to limited capacity of WWTPs to treat the high volume of stormwater and wastewater received, the excess volume is released into freshwater bodies and coastal waters as untreated sewer overflow. This situation leads to significant pollution of the receiving water bodies. Therefore, they become contaminated with high concentrations of virus and bacteria-laden sediments, metals, and polycyclic aromatic hydrocarbons (PAHs). These pollutants reduce dissolved oxygen of the receiving water bodies and are toxic to aquatic organisms.

Besides, the pathogens in the polluted water bodies directly infect humans when they swim or play in contaminated beaches and rivers or consume water from such waterbodies. On the other hand, indirect infection occurs through the consumption of fishes and crustaceans harvested from contaminated rivers and seas. Another route of indirect infection is through the consumption of vegetables and crops irrigated with poorly treated or untreated water. Direct infection can also take place through close contact with and consumption of zoonotic domesticated, agricultural or wild animals. Furthermore, the occurrence of such infections on a large scale can lead to an epidemic outbreak and pathogen shedding by infected individuals (into the sewer network. In order to break the pathogen cycle in a sustainable manner, transmission pathways through WWTP, recreational contact, irrigation and aquaculture, contaminated drinking water, faulty drainage and poor ventilation systems in buildings should be blocked besides isolation and treatment of infected individuals and vaccination.

The top ranked keyword in cluster 3 is "aerosols", which is often underestimated in disease transmission. Aerosolized transmission of pathogens, such as antibiotic-resistant *Pseudomonas aeruginosa* and *Pseudomonas putida*, has been reported in previous studies (Gormley et al., 2017; Snitkin, 2019). Likewise, recent studies confirm aerosolized transmission of Covid-19 through air ducts in bathrooms, toilet facilities, and wastewater discharged from WWTPs (Ding et al., 2021; Gholipour et al., 2021; Hwang and Foster, 2008).

Table 1. Top keywords based on highest number of occurrences

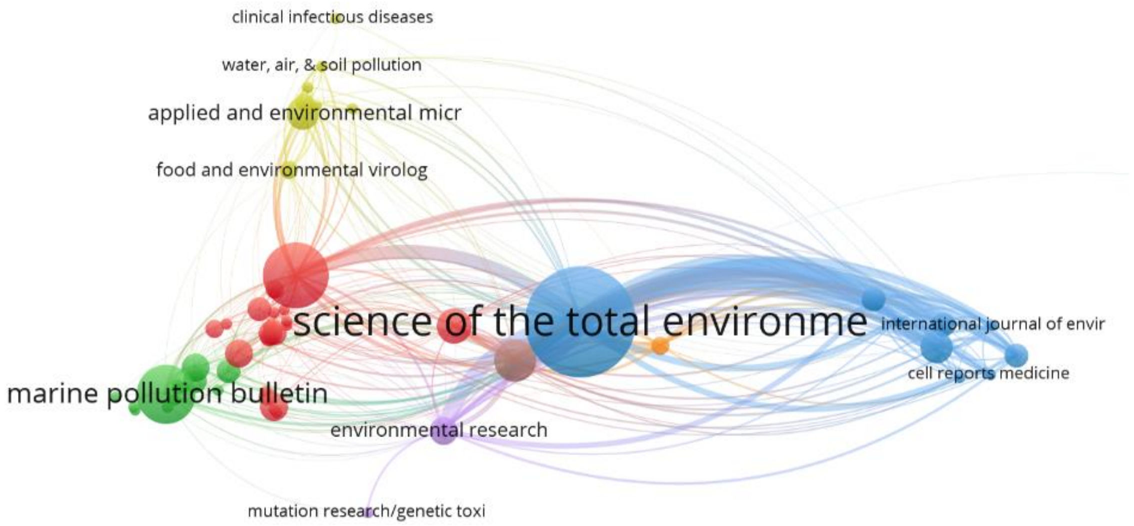
Keywords	Occurrences	Total link strength
Non-human	62	1873
Environmental monitoring	61	1868
Sewage	57	1426
Wastewater treatment	57	1417
Water quality	53	1082
Human	45	1426
Covid-19	43	1119
Water pollution	43	941
Controlled study	40	1166
Viruses	38	1122
Sars-COV-2	36	884
Wastewater	35	1179
Rivers	35	895
Combined sewer overflow	34	754
Sewer network	34	683
Combined sewers	33	764
Risk assessment	20	496
Public health	16	470

The top keywords based on occurrences and total link strength are displayed in Table 1. Based on highest total link strength, the top five keywords are "non-human", "environmental monitoring", "sewage", "wastewater treatment", and "water quality". The low number of occurrences of "public health" (16) and "risk assessment" (20) shows that limited research has been done in these areas. Non-human refers to animals and pathogens such as zoonotic domesticated, agricultural and wild animals, virus, bacteria, protozoa and fungi, etc that facilitate transmission of infectious diseases in humans. More than 60% of all known human pathogens are zoonotic which originate in animals but can cross-infect humans and 75% of new pathogens detected within the last three decades originated from animals (Taylor *et al*. 2001; Jones et al, 2008). Understanding their dynamic evolution as multi-host pathogens in terms of their evolutionary, environmental and climatic interactions is important to prevent or reduce their transmission and human infections. Therefore, environmental monitoring of sewage and wastewater treatment as well as water quality for domestic and industrial purposes and updating their various treatments are crucial to mitigating pathogen transmission and should be pursued and funded complementarily with vaccination.

3.2 Journal contribution analysis

In terms of journal contribution to the research on SO, *Science of Total Environment (STOTEM)* contributes 20.1% of all the assessed papers. This was followed by *Water Research* (8.5%) and *Marine Pollution Bulletin* (7%). Also, *STOTEM* has the biggest node (Figure 3(a)) and highest total network link strength (TLS) of 4684, as displayed in Table 2. Despite that *Water Research* publishes a lower number of research articles, its impact factor of 9.13 is higher than the 6.55 of *STOTEM*, as displayed in Figure 3(b).

Correlation analysis shows that TLS and citations are highly correlated with the number of published articles, each having a correlation coefficient, r = 0.869 and r = 0.795, respectively. On the other hand, citations is moderately correlated with TLS (r = 0.615) and impact factor (r = 0.508) (Sojobi, 2016). The higher impact factor of *Water Research* may be attributed to its higher co-citations of 557 and co-citation TLS of 46,019 when compared with *STOTEM's*, as shown in Figure 3(c). This implies that for any journal to increase its impact factor, it must prioritize increasing its co-citations, linkage with other journals and number of published articles. Out of the 21 publishing outlets, Elsevier tops the chart by publishing 30.9% of the assessed journals, followed by Springer 11.8%, Wiley 10.3%, and Taylor & Francis 8.8%. This implies these four publishers are responsible for 61.8% of the journals reviewed. In addition, 92.5% of these journals are hosted in England, USA, Netherlands, and Germany.


clinical infectious diseases
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marine pollution bulletin
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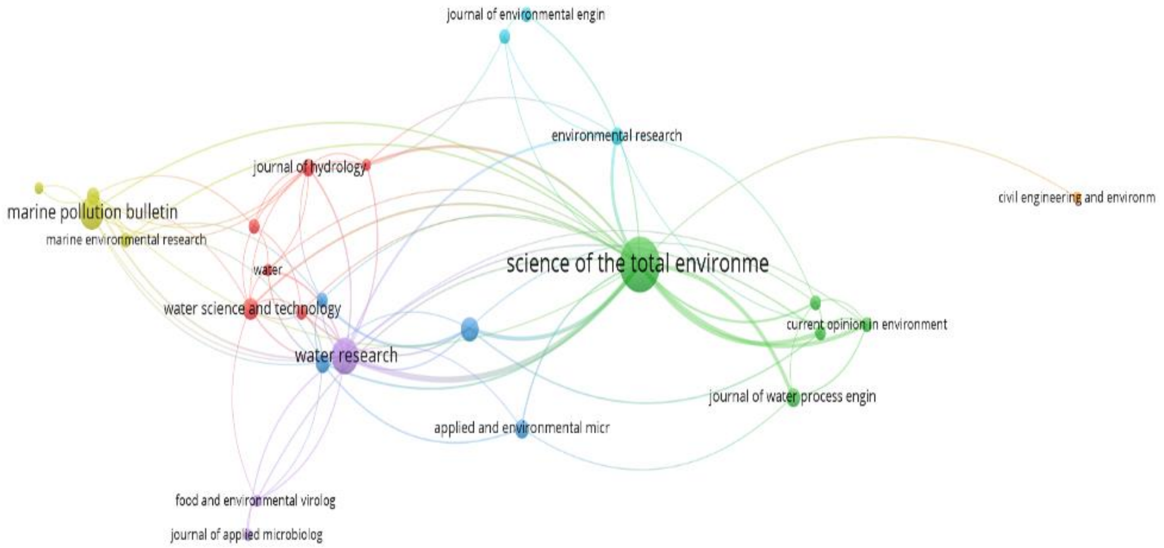
(a)


journal of environmental engin
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marine pollution bulletin
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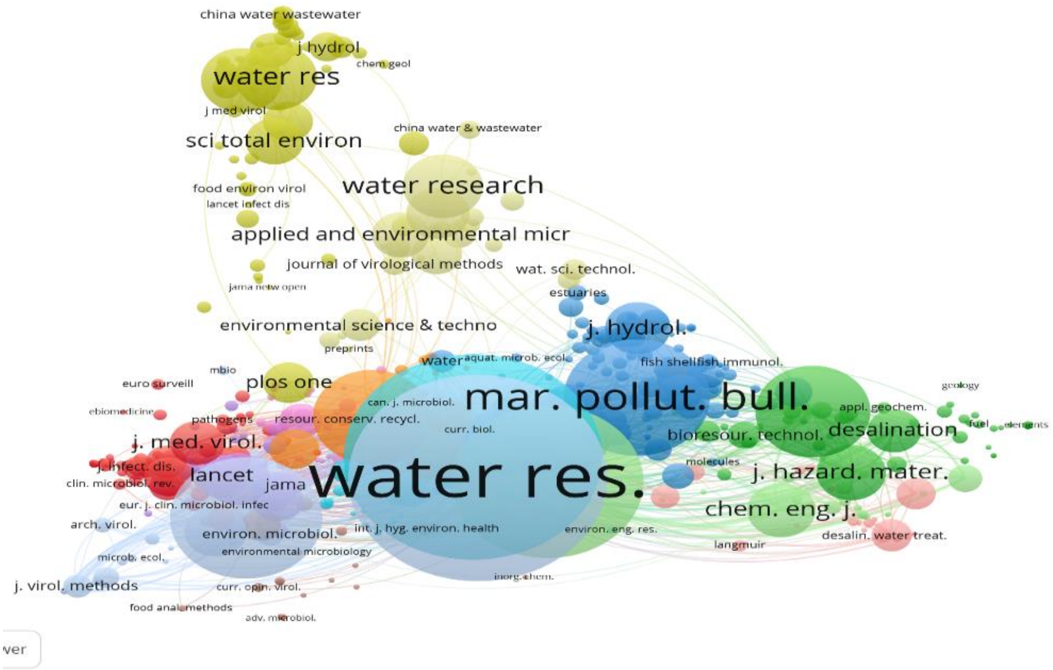


(c)

Figure 3. (a) Network of journal contribution. (b) Publication outlets by documents (c) Publication outlet based on co-citations

Table 2. Top 10 journals based on number of documents

Journal	Docs	Citations	Total link strength	Impact Factor	Publisher	Host country
Science of the total environment	40	743	4684	6.551	Elsevier	Netherlands
Water research	17	967	896	9.13	Pergamon-Elsevier Sci. Ltd	England
Marine pollution bulletin	14	184	181	4.049	Pergamon-Elsevier Sci. Ltd	England
Chemical engineering journal	8	374	1320	10.652	Elsevier Science SA	Switzerland
Water Science & technology	6	56	273	1.638	IWA	England
Environmental Science & Technology	5	486	0	7.864	IWA	England
Journal of Water Process Engineering	5	88	1188	3.465	Elsevier	Netherlands
Applied and Environmental Microbiology	5	258	208	4.016	Amer Soc Microb.	USA
Environmental Research	4	73	892	5.715	Academic Press Inc Elsevier Sci	USA
Journal of Hydrology	4	109	78	4.5	Elsevier	Netherlands

NB: IWA = IWA Publishing; Amer Soc Microb. = American Society for Microbiology

3.3 Authors' citation network, co-citation network, and document citation density

Author’s citation network analysis revealed 10 clusters, which were displayed in Figure 4. Cluster 1 (red) is represented by Jones D. I. with 16 items, and cluster 2 (green) is represented by Harwood V. J. with 15 items. Also, Bertsch P. M., Kitajima M., and Carducci A. are in clusters 3 (blue, 14 items), 4 (light aquamarine, 14 items), and 5 (medium purple, 9 items), respectively. In addition, clusters 6 (turquoise), 7 (orange), and 8 (dark brown) have Ahmed W. (7 items), Scherchan S. P. (6 items), and Rose J. B. (6 items), respectively. Lastly, Bibby K. is in cluster 9 (pink, 6 items), while Haramoto E. is in cluster 10 (light coral, 3 items). The authors with the highest co-citation/publication network in terms of node size are Kitajima M, Ahmed W, Haramoto E, Katayama H., and Bibby K.

Co-citation networks analysis also revealed that Kitajima M. had the biggest node in terms of co-citation with the highest TLS of 22 due to his collaborations with several top authors. These top authors include Haramoto E., Ahmed W., Rose J. B., and Bibby K. Therefore, it is expedient for researchers to establish research network with several active researchers in their field or related fields. As shown in Table 3, the co-citation network is favourable to both Haramoto and Kitajima as their recent papers ranked among the top 10 highly cited papers.

Kim et al. (2018)), with the highest number of citations (163), examined the removal of emerging contaminants in wastewater and water. The second highly cited paper (Zgheib et al., 2012) investigated the adsorption of priority contaminants, such as metals and PAHs, to sediments in urban stormwater. The paper revealed that the discharge of untreated SO poses serious risk of polluting the receiving water with highly contaminated sediments. The third highly cited paper by (Jiang, 2006) reviewed worldwide occurrence and health implications of adenovirus. The paper showed that adenovirus infection can be acquired through the consumption of contaminated water and aerosolized droplets during swimming in recreational waters, such as public swimming pools and coastal waters.

The fourth highly cited paper (Passerat et al., 2011) investigateed the impact of SO on receiving waters during intense rainfall for both dry and wet seasons. The study established significant microbial and physical degradation of the receiving water due to resuspension, transport, and discharge of microbial-imparted sediments, especially during the wet season. An earlier study reported the presence of human adenovirus and human polyomavirus in a river due to contamination with human sewage (Hamza et al., 2009). The authors warned of the potential public health concerns that result from the cross-reaction between human and animal viruses.

Figure 5 showed document citation density map. The top highly cited articles appear in yellow. These documents contain the basics of research on SO and public health. Also, as shown in Table 5, 61.8% of the papers reviewed in this study are published by Elsevier (30.9%), Springer (11.8%), Wiley (10.3%), and Taylor & Francis (8.8%).

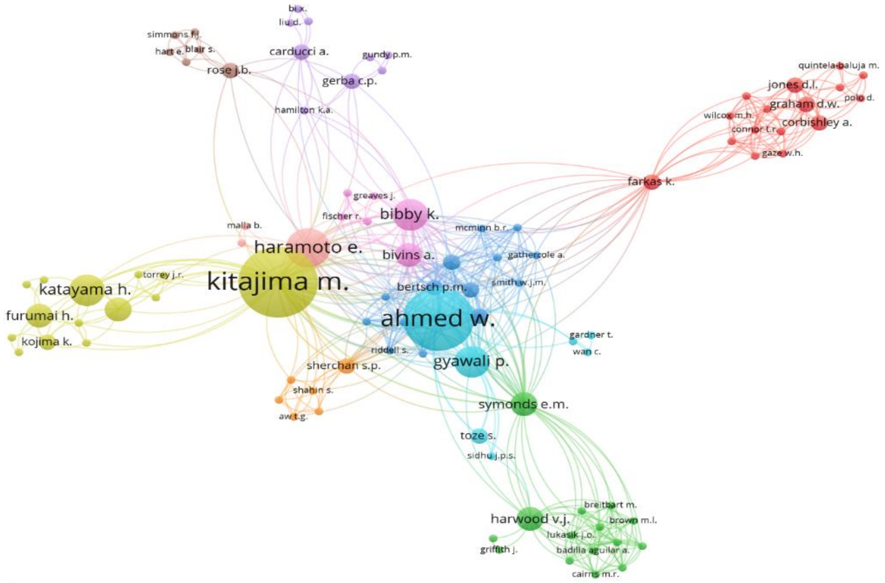


Figure 4. Clusters of authors citation/publication network

Table 3. Top 35 highly cited articles based on web of science metric

S/N	Article	Citations	S/N	Article	Citations	S/N	Article	Citations
1	Kim (2018)	163	13	Fries (2016)	82	25	Bonneau (2017)	54
2	Zgheib (2012)	159	14	Kuo (2010)	77	26	Costa (2011)	53
3	Jiang (2006)	136	15	Gasperi (2012)	75	27	Caplin (2008)	52
4	Passerat (2011)	132	16	Weyrauch (2010)	73	28	Ahmed (2015)	52
5	Hamza (2009)	118	17	Hata (20130	72	29	Sherchan (2020)	48
6	Phillips (2012)	116	18	Askarizadeh (2015)	71	30	Muthukamaran (2011)	49
7	Buerge (2006)	114	19	Even (2007)	70	31	Ryu (2011)	45
8	Haramoto (2018)	107	20	Haramoto (2020)	61	32	Kumar (2020b)	43
9	Kitajima (2020)	104	21	Chu (2017)	58	33	Lee (2012)	43
10	O'reilly (2007)	96	22	Cabral (2012)	47	34	Bofill-mas (2013)	42
11	Joseph (2019)	89	23	Ahmed (2020b)	57	35	Einsiedl (2010)	42
12	Gasperi (2012)	82	24	Costa (2008)	57			

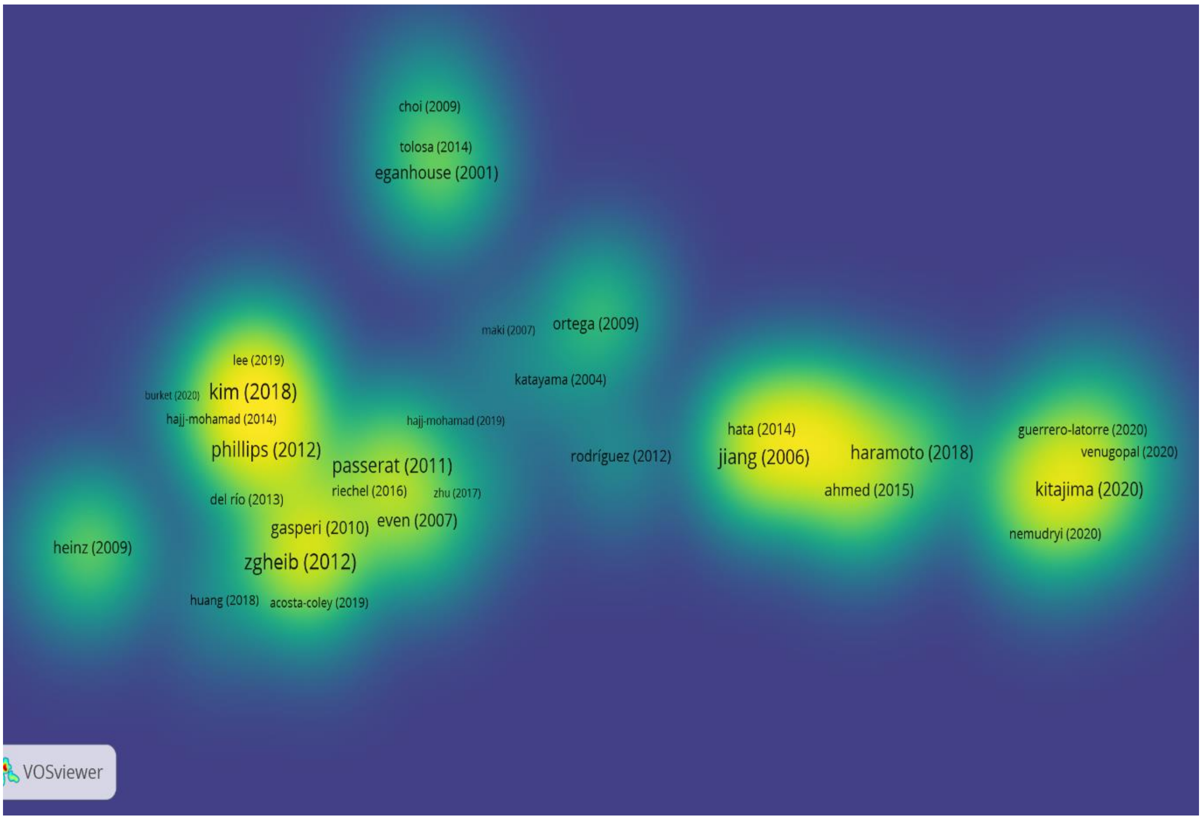


Figure 5. Document citation density

3.4 Country analysis

In terms of publications, the top six countries in the areas of SO and public health are the USA, China, Spain, Australia, Japan, and Canada with 53, 23, 19, 18, 16, and 15 publications, respectively. Country analysis by co-authorship also revealed that the USA has the biggest node, followed by China and Spain, as displayed in Figure 6. Also, there are ten country clusters in Figure 6. Cluster 1 comprises Brazil, Finland, Mexico, New Zealand, Switzerland, Taiwan, and Vietnam. Cluster 2 includes Colombia, Ecuador, Portugal, Spain, and Romania. Belgium, Canada, France, Luxembourg, and Ireland form cluster 3, while cluster 4 consists of Austria Denmark, Ethiopia, Germany, and Kenya. In cluster 5, there are India, Indonesia, Israel, Netherlands, and Singapore. Furthermore, cluster 6 consists of China, Hong Kong, Nigeria, Saudi Arabia, and South Korea. Similarly, Egypt, Italy, Japan, and Thailand comprise countries in cluster 7, whereas Malaysia, Qatar, UAE, and UK make up cluster 8. In cluster 9 are Australia, Bangladesh, and Sri Lanka, while Costa Rica and the USA are found in cluster 10. Therefore, there are 48 countries in all the clusters. This implies that only few countries are involved in studies on SO in relation to public health.

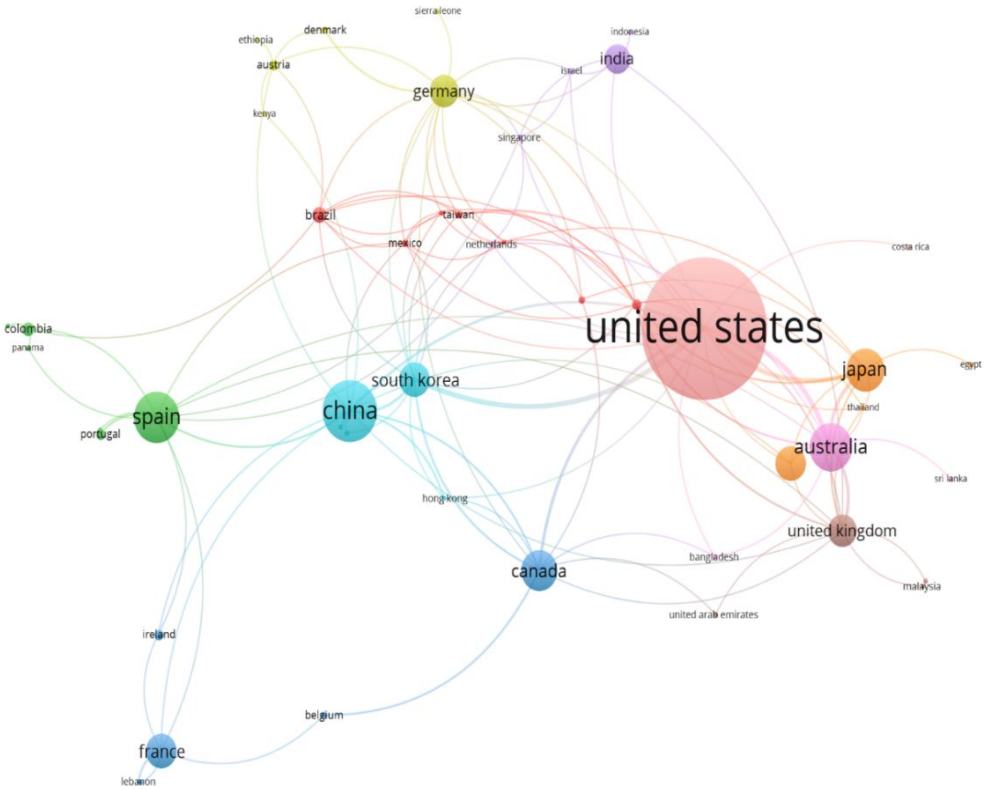


Figure 6. Co-authorship network by country

4. Systematic review

A systematic review of the retrieved literature showed that six methodological approaches have been applied to the study of SO, as portrayed in Figure 7. Majority of the studies (49%) utilized field sampling and laboratory experiments, whereas review papers and modelling studies were 24% and 15%, respectively. In addition, about 5% of these papers used a hybrid method by combining both experimental and modelling approaches.

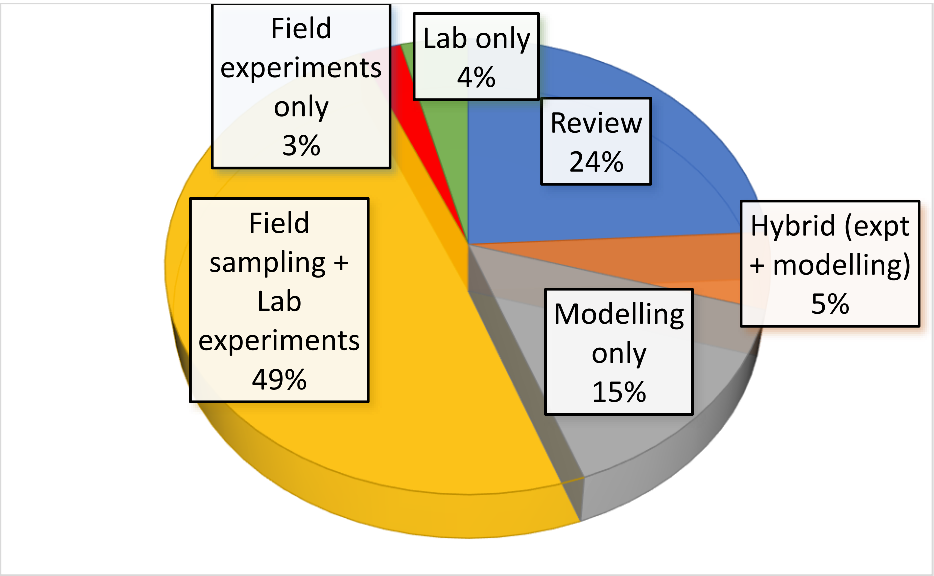


Figure 7. Breakdown of methodological approaches

4.1 Combined field sampling- and laboratory experiment-based studies

In this category (Table 4), field samples were taken from the field for laboratory testing. Field samples are usualy taken from diverse places, such as inlets, outlets, and within WWTP, SO outfalls, rivers, seawater, estuaries, and bays. Other sources include harbours, beaches, pump, hospital wastewaters, drainage systems, septic tanks, manholes, farms, drinking water treatment plants (DWTPs), air, and toilet surfaces. Four kinds of tests have been reported in the literature, as shown in Figure 8(a). Microbiological analyses are the most frequently used testing method to determine the microbiological compositions of sewage, SO, and associated impact on a sewer network and receiving waters. Pathogenic organisms of concerns are Covid-19 RNA (ribonucleic acid), *E. coli*, intestinal enterococci, enteric adenovirus, norovirus, and enterovirus. Others include human polyomaviruses (HPyVs) and papillomaviruses (HPVs), Aichi viruses, somatic coliphages, salmonella, and norovirus genogroup 1 (NoVG1) to mention a few. Accurate understanding of the microbial (pathogen) type and its concentration is useful for designing appropriate treatment system in the WWTP. In addition, such knowledge is useful to guide the selection of sourcewater intake for irrigation and public water supply.

Physico-chemical analyses was ranked as the second highest used tests. These tests focused on physico-chemical properties of sewer overflow, such as turbidity, salinity, heavy metals, PAHs, pharmaceuticals, and personal care products. Furthermore, combined physico-chemical and microbiological analyses approach seeks to decipher the relationship between physico-chemical parameters and microbiological indicators. Often, some correlations were found between some physico-chemical parameters and microbial indicators. On the other hand, the least popular test is the hybrid physico-chemical and biological analyses. This test focused on ascertaining the toxicity and genotoxicity of SO contaminants on selected aquatic organisms, such as fishes, oysters, and mussels. However, this method is seldom employed because it is capital, human, and equipment intensive. However, it is crucial to understanding the impact of SO contaminants. Therefore, more studies on physico-chemical and microbiological analyses are required to show the importance of SO on aquatic organisms living in impacted water bodies and humans who utilized the water bodies for recreation, public water supply and irrigation.

Analysis of these studies showed that various recovery and detection methods have been used for Covid-19 RNA, which makes comparison difficult. Most studies utilize quantitative real-time reverse transcription polymerase chain reaction (RT-qPCR) to quantify pathogens identified in wastewater. With respect to pre-treatment for recovery purposes, a recent study reported that there is no need for pre-treatment of wastewater (WW) samples to improve the recovery of Covid-19 RNA (Ahmed et al., 2020a). Removal of pre-treatment requirement ensures rapid, accurate and cost-effective detection of Covid-19 RNA in wastewater specimen. For the detection of Covid-19 RNA in WW, several authors have used different assays (analytes), such as Taqman assay (Mlejnkova et al., 2020), N assay, and Orf1b assay (Baldovin et al., 2021). Other assays include duplex (Kitamura et al., 2021) and Taqpath (Kumar et al., 2020b), which are quite effective in detecting Covid-19 RNA in WW. However, E gene and N gene are more effective analytes in Covid-19 RNA detection compared to RdRp, Orf1ab and S genes (Arora et al., 2020). Another study also reports that ORF1ab, N protein genes, and S protein genes output similar C_T values (Kumar et al., 2020a). These above results imply that future studies are required to streamline and standardize the recovery and detection methods (protocols) in wastewater-based epidemiology (WBE) to facilitate a comparison of various WBE researches. In addition, Covid-19 RNA has been detected in wastewater between 2 days and 3 weeks before any clinical report of Covid-19 (Nemudryi et al., 2020; Trottier et al., 2020).

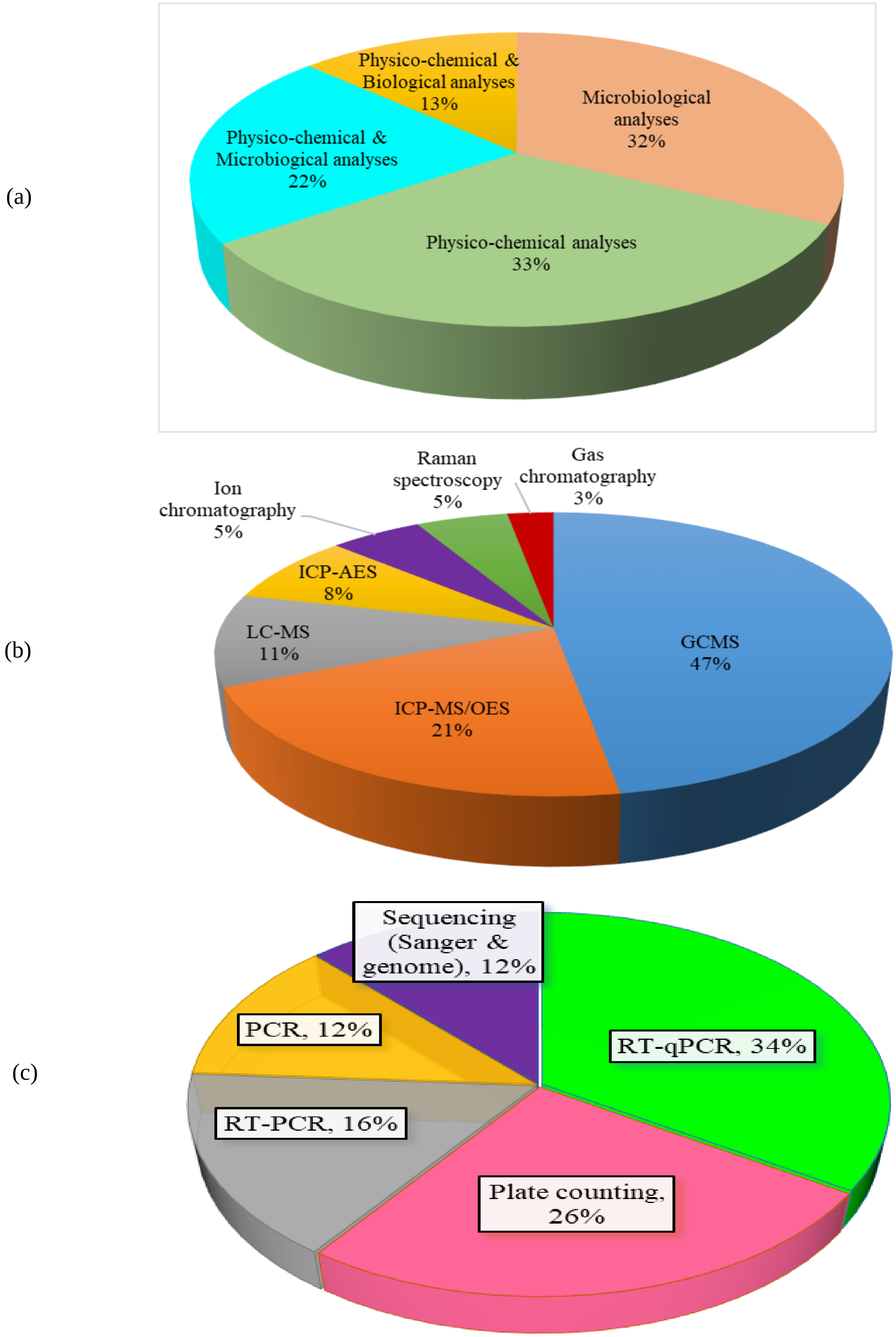


Figure 8 Breakdown of (a) field sampling and laboratory approach; (b) physico-chemical analyses methods; and (c) biological/microbiological methods

Figure 8 (b) displayed the breakdown of the physico-chemical analysis methods. GC-MS (gas chromatography-mass spectrometry) has been applied in quantifying contaminants in aquifer and marine waters, and sediments. (Costa et al., 2011; Schertzinger et al., 2019b). The contaminants analysed include organic pollutants, such as PAH, PCB (polychlorinated biphenyls), pesticides, and hydrocarbons. Alongside, special biomarkers (such as coprostanol) and bioassay have been used to quantify an increase in pollution concentration during SO as well as the genotoxic effects (Jeon et al., 2017; Whaley-Martin et al., 2017). Spearman rank correlation, principal component analyses (PCA) and correspondence analyses have been utilized to reveal the source of contamination and establish the relationship between sediment contaminants and genotoxicity (Choi et al., 2009; Costa et al., 2008).

ICP-MS (inductively coupled plasma mass spectrometry) is useful for the quantification of non-metals, metalloids and metals, major cations, and trace elements in marine waters, marine sediments and their distribution (Kontchou et al., 2021; Valdelamar-Villegas et al., 2021). ICP-MS is also used to confirm their bio-accumulation in aquatic organisms during SO. ICP-AES (inductively coupled plasma atomic emission spectrometry) provides a robust, rapid, multi-element analysis of solutions. This technique has been applied to detect the presence of heavy metals and trace elements in water, stormwater and sediment samples (Garcia-Seone et al., 2016; Gasperi et al., 2010). ICP-AES is also called ICP-OES (inductively coupled plasma optical emission spectrometry). However, its limitations include unsuitability for halogens and inert gases, higher limit of detection, and inaccurate identification due to spectral overlap. Other limitations include higher cost and expert requirement compared to ICP-MS (Levine, 2021; Olesik, 2020). While ICP-AES is better for analysing TDS, ICP-MS has a higher sensitivity (ppt) due to the use of mass-spectral techniques compared to ICP-AES, which relies on photon emission (Levine, 2021).

Furthermore, LC-MS (liquid chromatography-mass spectrometry) is applied to simultaneously analyse a broader range of compounds compared to GC-MS, and has high sensitivity and specificity (Pitt, 2009). LC-MS has been applied to detect and quantify micro pollutants, such as endocrine disrupting compounds (EDC) and pharmaceutical and personal care products (PPCP). Others include alkylphenols in wastewater and sediments in sewer network, rivers, and WWTP effluent, SO outfalls and fish tissues (Burket et al., 2020; De los Rios et al., 2012; De Melo et al., 2019; Einsiedl et al., 2010; Hajj-Mohamad et al., 2019; Ryu et al., 2014). Hierarchical analyses and cross-connection index have also been applied to characterize the contamination level, its potential source and prioritize remediation (De Melo et al., 2019; Hajj-

Mohamad et al., 2019). The limitations of LC-MS are its high initial costs, ion suppression, and reproducibility limited to stable internal standards.

In addition, ion chromatography has been recognized as a global reference method for analysing anions and cations in environmental samples, such as water and wastewater (Jackson, 2020; Michalski, 2018). It has been applied in the analyses of major ions including Ca^{2+}, HCO_3, Na^+, and inorganic ions (Einsiedl et al., 2010; Heinz et al., 2009). Its advantages include reliability, high accuracy and precision, high selectivity, high speed, high separation efficiency, and low cost of consumables. Further developments are required for full automation, to extend its applications, improve speed and ion selectivity, lower limits of detection and quantification (Michalski, 2018).

Figure 8 (c) showed the breakdown of the hybrid biological and microbiological methods. While traditional PCR focuses on end-point detection, RT-PCR (real-time PCR) focuses on detection of PCR amplification from the early phases and throughout the reaction phases to the end of reaction. Also, while RT-PCR is semi-automated, RT-qPCR is fully automated and facilitates fast detection and quantification of pathogens, including Covid-19. The disadvantages of traditional PCR are low precision and sensitivity and non-automation. The major disadvantages of both RT-PCR and RT-qPCR are requirement of capital-intensive equipment, time-consuming, labour intensive, and limitations of inadequate supply of RNA extraction kits and relatively scarce qPCR machines (Esbin et al., 2020).

Sanger sequencing (SS) is useful for detection of pathogen mutations and has been utilized in the identification of Covid-19 variant in WWTP and antibiotic-resistant pathogens in plumbing systems (Snitkin, 2019; Westhaus et al., 2021). Compared to SS, genome sequencing (GS) is faster, requires less personnel and less space requirements, and has higher throughput and cost-effective. GS has been applied in the identification of various virus strains in WW and cluster identification (Du et al., 2020; Grada and Weinbrecht, 2013; Nemudryi et al., 2020; Schuster, 2008). The major disadvantages of GS are high initial capital cost, sequencing errors, and time-consuming data analysis. To maintain high accuracy, recent studies recommend combining SS and GS (Baudhin et al., 2015; Mu et al., 2016; Okada et al., 2020).

Plate counting relies on manual counting of colonies of fecal coliforms, which grow on plates (dish) after specific incubation period and temperature. Plate counting has been used to detect and quantify bacteria, fecal and total coliforms in river water, wastewater and public facilities (Glinska-Lewczuk et al., 2016; Hata et al., 2014; Kotay et al., 2019). Analysis of the results with PCA and cluster analyses revealed anthropogenic pollution from WWTP, and the pollution level did not exhibit seasonal variation. However, plate counting is unsuitable for virus detection and quantification (Hata et al., 2014). Alternatively, most probable number (MPN) method can be utilized as a substitute for plate counting. MPN has been applied in quantifying fecal indicators in estuarine water and mussel tissues (De los Rios et al., 2012; Fries et al., 2006). Though a study reports comparable results from both methods, however MPN method is less labour-intensive (Hunsinger et al., 2005).

512 Table 4. Summary of studies that combine field sampling with laboratory experiments

Category	Summary/Remark	References
Physico-chemical analyses	Major contaminants transported during SO are persistent in nature and include heavy/trace metals, PAHs, PCBs, DDTs, DEHP, VOC, PPCPs and plastics. Source control, pre-treatment of SO and environmental monitoring are recommended, while sucralose, coprostanol and caffeine are prescribed for contaminant tracing.	(An et al., 2020; Buerge et al., 2006; Cantwell et al., 2019; Choi et al., 2009; De Melo et al., 2019; Eganhouse and Sherblom, 2001; Einsiedl et al., 2010; Garces-Ordonez et al., 2020a; Gasperi et al., 2011; Gasperi et al., 2010; Gasperi et al., 2012; Glinska-Lewczuk et al., 2016; Hajj-Mohamad et al., 2019; Hwang and Foster, 2008; Jeon et al., 2017; Lazzari et al., 2019; Lopez-Ponnada et al., 2017; O'Briain et al., 2020; Oppoeinheimer et al., 2012; Qibo et al., 2016; Rio et al., 2013; Ryu et al., 2014; Schertzinger et al., 2019a; Schertzinger et al., 2019b; Tolosa et al., 2014; Valdelamar-Villegas et al., 2021; Whaley-Martin et al., 2017; Yilma et al., 2018; Zgheib et al., 2012)
Microbiological analyses	Studies advocate environmental protection through improved water and WWT plans, public enlightenment, and enhanced WBE surveillance due to detection of Covid-19 in WW. Fecal-derived aerosols and fomite dominate Covid-19 transmission. Standardized protocol for Covid-19 is required.	(Ahmed et al., 2020a; Ahmed et al., 2020b; Ahmed et al., 2016; Ahmed et al., 2015; Ahmed et al., 2010; Arora et al., 2020; Baldovin et al., 2021; Balleste et al., 2019; Caplin et al., 2008; Carrillo-Reyes et al., 2020; Ding et al., 2021; Ham et al., 2009; Hamza et al., 2009; Haramoto et al., 2020; Iaconelli et al., 2015; Kotay et al., 2019; Kumar et al., 2020a; Kuo et al., 2010; La Rosa et al., 2021; McQuaig et al., 2012; Mlejnkova et al., 2020; Nemudryi et al., 2020; O'Reilly et al., 2007; Ogorzaly et al., 2010; Osuolale and Okoh, 2015; Randazzo et al., 2020; Sherchan et al., 2020; Siddiqee et al., 2020; Snitkin, 2019; Trottier et al., 2020; Westhaus et al., 2021)
Physico-chemical & Microbiological analyses	SO increases pathogen concentration by 127-2387% due to sediment resuspension. Pre-treatment of SO is recommended to reduce sediments and pathogens. Environmental surveillance of rivers, beaches and drinking water sources to minimize public health risk is urgent.	(Al Aukidy and Verlicchi, 2017; Burnet et al., 2019; Daly et al., 2013; Fries et al., 2006; Gonzalez-Fernandez et al., 2021; Guerreo-Latorre et al., 2020; Hajj-Mohamad et al., 2019; Hata et al., 2014; Jeanneau et al., 2012; Katayama et al., 2004; La Rosa et al., 2015; Lee et al., 2012; Maki et al., 2007; Ogorzaly et al., 2009; Ortega et al., 2009; Passerat et al., 2011; Rodriguez et al., 2012; Toriman et al., 2018; Weyrauch et al., 2010; Wu et al., 2019; Zhang et al., 2014)

Physico-chemical and Biological indicators	Contaminated sediments promote bioaccumulation of organic and metallic contaminants in aquatic organisms resulting in genotoxic effects and biodiversity reduction. Also, it is important to avert marine plastic pollution.	(Acosta-Coley et al., 2019; Bach et al., 2009; Blalock et al., 2020; Burket et al., 2020; Costa et al., 2008; Costa et al., 2011; De los Rios et al., 2012; Garces-Ordonez et al., 2020b; Garcia-Seone et al., 2016; Morelle et al., 2017; Prato et al., 2015; Zacchi et al., 2018)

4.2 Review-based studies

Occurrences of coronavirus 1 (SARSCoV-1) in 2003, Eastern respiratory syndrome coronavirus (MERS-CoV) in 2012, and Ebola virus in 2014 were forewarnings to the recent Covid-19 outbreak. The contagious nature, persistency and mutation of Covid-19, illegal trade of endangered species, and expanding global travels make the containment of Covid-19 very difficult (Elsamadony et al., 2021). Furthermore, the spread and containment of outbreaks (particularly Covid-19) depend on the level and timeliness of control measures, environmental conditions, treatment facilities, and social conditions (Arslan et al., 2020). Co-infection with fungal, bacterial, influenza, and other diseases increases health risks by reducing the immunity of infected patients (Jones et al., 2020b).

The natural environment, which serves as the mediator for pandemics, has been inadequately explored (Ji et al., 2021). A recent study reported that majority of infections are transmitted in an indoor setting or in a transportation system (Mohapatra et al., 2021; Qian et al., 2020). Seven potential pathogen transmission routes have been identified, as shown in Figure 9 (a). The largest four modes of transmission based on mentions in some review-based studies are sewage/wastewater (30%), aerosol (21%), fecal-oral (20%), and skin/surface transmissions (14%) (Arslan et al., 2020; Cahill and Morris, 2020; Dharma et al., 2021; Elsamadony et al., 2021; Ji et al., 2021; Jones et al., 2020b; Kitajima et al., 2020; Mohapatra et al., 2021). This implies greater attention should be given to the sewage/wastewater transmission routes which has been grossly underestimated.

Sewage/wastewater transmission occurs during direct contact with untreated or poorly-treated sewage containing pathogens from infected persons either due to the use of shared public facilities or during caregiving. Transmission also occurs while working at WWTP, during maintenance of sewer/plumbing systems and through the use of untreated/poorly treated sludge/wastewater for farming. In addition, fecal-oral transmission results from the consumption of contaminated water from poorly maintained and inadequately treated water distribution systems (Arslan et al., 2020).

Likewise, aerosol transmission can be caused by poor ventilation and plumbing systems in residential buildings, hospitals, commercial complexes and restaurants, and transportation systems. It also occurs through direct contact with respiratory droplets and is prevalent in countries with poor outdoor air quality (Kitajima et al., 2020). A recent study reveals that although Covid-19 droplet is highly transmissible under favorable temperature and humidity conditions, face masks are effective in reducing transmission in both outdoor and indoor environments (Zhao et al., 2020). Aerosol transmission also occurs in WWTPs and surrounding communities (Gholipour et al., 2021; Pasalari et al., 2019).

Skin/surface transmission occurs through direct contact with infected surfaces and recreational waters (Cahill and Morris, 2020; Jones et al., 2020b; Liu et al., 2020; Saawarn and Hait, 2021). Transmission through marine foods/vegetables occur from consumption of poorly cooked aquatic foods harvested from infected waters and uncooked vegetables irrigated with contaminated water. Vector transmission is caused by rodents and insects in residences and restaurants, while solid waste transmission is attributable to direct contact with solid wastes generated by infected persons and human cadavers.

Percentage distribution of the research focus of the assessed papers are shown in Figure 9 (b). The most popular research focus is on Covid-19 (71%), followed by adenovirus, norovirus and polyomavirus (10%), bacteria and protozoans (5%), and plastic wastes (5%). Measures recommended to mitigate pathogen transmission and improve public health are also listed in Figure 9 (c). The top three measures comprise optimized treatment of water and wastewater (32%), promotion of point-of-use treatment (POUT) and water, sanitation and hygiene (WASH) (19%), and surveillance (17%). Other measures include enforcing the use of PPEs, such as face masks, improving solid waste management, and formulating enabling policies and social interventions. Policy and social interventions may include social distancing and lockdowns, restriction of recreational activities in contaminated beaches, and providing welfare packages for low-income earners. While most efforts and funding have been chanelled towards healthcare and social interventions in terms of vaccination, lockdown and facemasks, greater research efforts and funding should be directed towards optimization of water and wastewater treatment, publicity of point-of-use water treatment as well as WASH to curb ongoing pandemic in a cost-effective sustainable manner. Point-of-use water treatment and personal hygiene have been found effective in mitigating bacterial, viral and protozoan waterborne pathogens (Abbaszadegan et al., 1997; Brown and Sobsey, 2012; Clasen et al., 2008; Doocy and Burnham, 2006; Sojobi et al., 2014; Sojobi et al., 2015)

It is also important to improve ventilation in buildings and enforce good plumbing practices to minimize aerosol-pathogen transmission and promote high-impact collaborative research. Prevailing poor design and maintenance of ventilation, air condition and plumbing systems facilitate rapid pathogen transmission in high occupancy, high rise buildings (Correia et al., 2020; Lin et al., 2021; Lipinski et al., 2020). Therefore, to provide safe indoor environments, present buildings need to be redesigned to avoid connections between rooms via ventilation systems and discontinue the use of centralized ceiling ventilation systems (Pease et al., 2021; Tang et al., 2006).In addition, monitoring should be put in place to ensure compliance and regular maintenance of updated ventilation and plumbing systems in existing public and private buildings and future building projects.

Investment in vaccine development is also important to improve community immunity against pathogens. While vaccine deployment is necessary to prevent high mortality, severe economic disruption and major adjustment to our way of life (Graham, 2020), due considerations must be given to avoid common pitfalls of vaccine developments such as antibody-dependant enhancement, low vaccine safety, rapid decline of antibodies and low vaccine efficacy in neutralizing Covid-19 mutants. Considering the huge cost of vaccine development and the short timeframe, the various trials need to be carefully designed to make the most of the derived data without violating regulatory requirements. Scaling up vaccine mass production and delivery to all regions of the world poses a logistic challenge (Flanagan et al., 2020) that can be overcomed through intergovernmental and inter-private organizational co-operations.

Combination of molecular imaging and serial CT imaging with artificial intelligence, clinical data and genomic studies, and combination therapy of selected vaccine candidates and natural medicine simultaneously is important to make the most of vaccine investment and human labours for optimized, efficient and vaccine development (Ciabattini et al., 2020; Damena et al., 2019; Katal et al., 2021; Ren et al., 2021; Wang et al., 2021a). Such integrative and multidimensional approach provide functional insights beyond limited human knowledge and provide predictive biological and mathematical models based on AI/machine/statistical learning to be developed to support rational and effective vaccine development and precision medicine which takes into account differences in individual susceptibility to disease and severity of illness (Ciabattini et al., 2020; Damena et al., 2019; Pereira et al., 2021). Besides, recent studies have revealed that combination of western medicine and traditional (natural) medicine recorded higher efficiency than vaccine alone in both moderate and critical cases owing to the bioactive compounds of natural medicine which improved cure rate and recovery, inhibited inflammation and improved lung conditions (Amaral-Machado et al., 2021; Dai et al., 2020; Huang et al., 2021; Liang et al., 2021; Ni et al., 2020; Wang et al., 2021a; Zhang et al., 2020). A recent study recommended the use of gene ontology enrichment analysis, compound target network analysis, gene network analysis and cytoscape analysis to unravel the virogenomic signatures and identify potential vaccine and natural medicine compounds for effective vaccine development (Muthuramalingam et al., 2020). To ensure equitable access, assistance should be given to low-income developing countries in Africa that may likely become the epicenter of the next wave of Covid-19.

Furthermore, several studies have reported the detection of Covid-19 in wastewater and sewage due to virus shedding in urine and faeces (Dharma et al., 2021; Kitajima et al., 2020; Saawarn and Hait, 2021; Tran et al., 2021). Covid-19 is persistent in wastewater and sewage (3 to 14 days) and CoV bioaerosols (up to 16 hours), which poses serious public health risks (Dharma et al., 2021; Kitajima et al., 2020). Therefore, it is important to limit recycling of sewage and application of wastewater in irrigation and organic fertilizer. The risk of Covid-19 infection is further heightened by inefficient WWT (wastewater treatment), leaking sewer pipes, plumbing systems and septic tanks (Ji et al., 2021). Prior to the emergence of the Covid-19 pandemic, WW pretreatment and recycling with bioaccumulation considerations are highly encouraged in irrigation (Al-Ghouti et al., 2019; Haramoto et al., 2018). However, the emergence of this pandemic has prompted several studies to recommend banning WW/sludge recycling for irrigation and recreational facilities (Arslan et al., 2020; Collivignarelli et al., 2020; Liu et al., 2020; Saawarn and Hait, 2021). Nevertheless, few studies advocate improving irrigation standards and disinfection to avoid the risk of food-chain transmission of Covid-19 (Dharma et al., 2021; Lahrich et al., 2021). Furthermore, some recent studies showed that Covid-19's major transmission route include fecal/urine-oral/ocular transmission through direct person-to-person contact and consumption of contaminated drinking water (Dharma et al., 2021; Jones et al., 2020b; Tran et al., 2021). In addition, potential Covid-19 transmission in wastewater to recreational waters has also been reported in another study (Cahill and Morris, 2020). Curtailing such transmission media poses a herculean challenge in both developed and developing countries. In addition, wastewater-irrigated agriculture portends another dangerous route for food-chain transmission through consumption of infected fishes and vegetables (Haramoto et al., 2018). To guarantee public safety, advanced and integrated multi-barrier approach is required (Mohan et al., 2021).

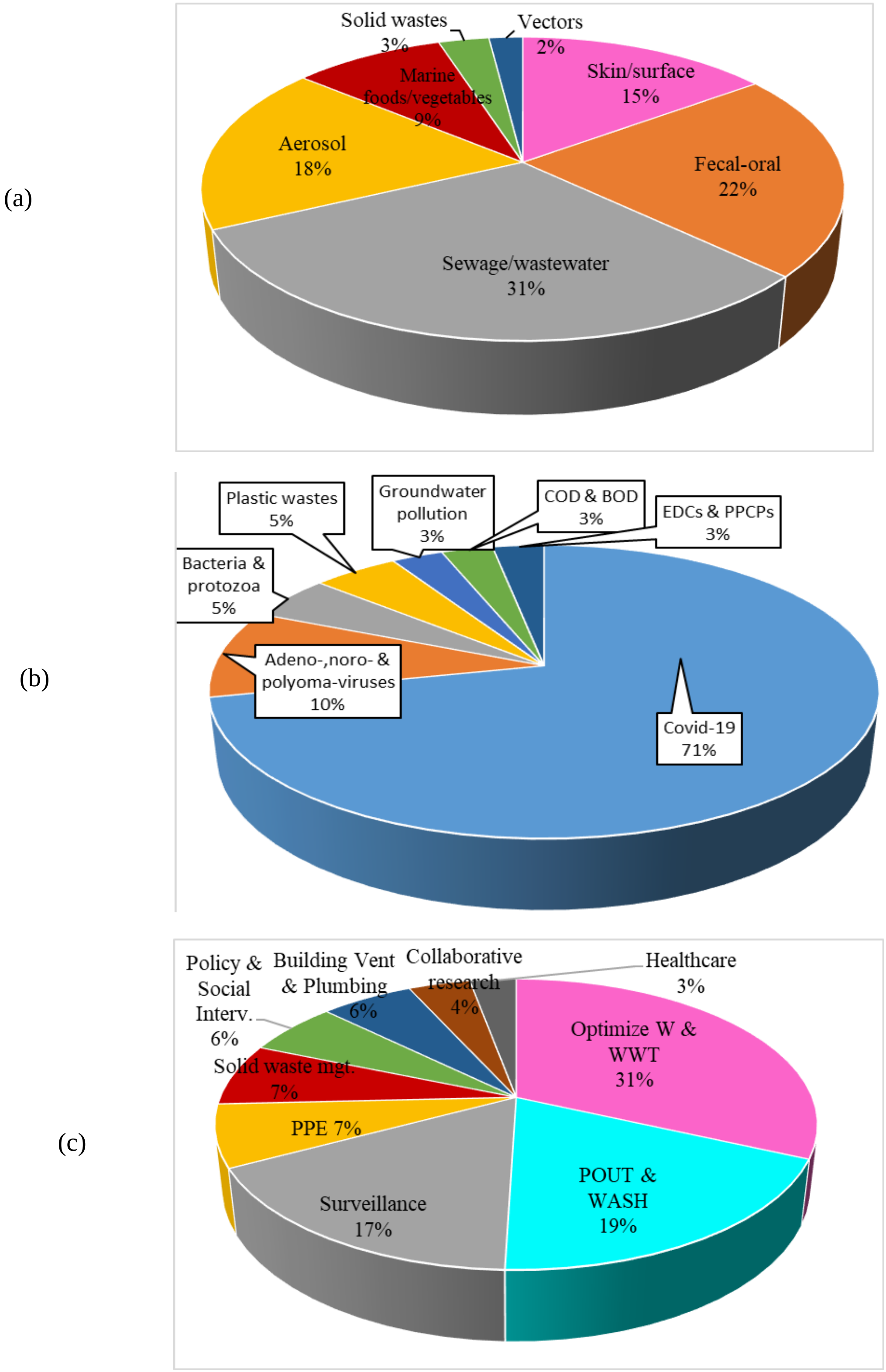


Figure 9. Percentage distribution of (a) potential pathogen (Covid-19) transmission routes; (b) research focus of reviewed papers; and (c) measures to mitigate pathogen transmission and improve public health

Covid-19 fatality and recovery depend on existing environmental conditions, innate immunity of infected persons, and associated health conditions (Kumar et al., 2020b). To improve environmental conditions, it is pertinent to maintain sewer networks, upgrade and optimize operations of WWTPs, improve community sanitation, and ban open defecation. Also, application of wastewater effluent for irrigation and ban on utilizing sewage sludge as fertilizer are recommended (Arslan et al., 2020; Kumar et al., 2020b; Lesimple et al., 2020; Liao et al., 2015; Mohapatra et al., 2021; Saawarn and Hait, 2021). Recent studies advocate tertiary WW treatment with NaClO and UV at appropriate dosage, high temperature between 56 and 70 ^{o}C, and longer retention time to eliminate the virus (Collivignarelli et al., 2020; Lahrich et al., 2021). Developing countries require external assistance in WWTP and solid waste management infrastructures, capacity development and policy interventions to mitigate high risk of Covid-19 transmission in Africa (Donde et al., 2021; Sunkari et al., 2021). To improve personal immunity, low-cost household water treatment processes, such as boiling of drinking water, public awareness on WASH (water, safety and hygiene), strict personal/hand hygiene, and mask wearing are recommended (Elsamadony et al., 2021; Jones et al., 2020b; Venugopal et al., 2020). A recent study also recommends cost-effective maintenance of sewer networks, construction of new sewer networks, and combined optimization of sewer network, WWTPs and DWTP (Huang et al., 2018).

To curtail the present Covid-19 pandemic and future pandemics, environmental surveillance is essential. WBE epidemiological surveillance is recommended alongside standard protocol for pathogen detection and quantification (Collivignarelli et al., 2020; Ihsanullah et al., 2021; Jiang, 2006; Mandal et al., 2020; Polo et al., 2020). However, environmental surveillance should encompass other infectious virus such as adenovirus, norovirus, polyomavirus, bacteria and protozoa, plastic wastes, groundwater pollution, COD (chemical oxygen demand and BOD (biological oxygen demand) which directly impact aquatic organisms, EDCs (endocrine disrupting compounds) and PPCPs (pharmaceuticals and personal care products) found in wastewaters and polluted surface waters, In addition, protection of drinking and recreational waters against aerosolized Covid-19 is important because Covid-19 survives longer in water than wastewater (Bivins et al., 2020; Mohapatra et al., 2021). Optimized and standardized protocol facilitates global comparison, creation of useful database and enhances research collaboration (Michael-Kordatou et al., 2020) (Michael-Kordatou et al, 2020). Environmental surveillance should cover waste, food, water, and funeral services. Also, social and healthcare institutions should be strengthened (Gwenzi, 2021). To minimize aerosolized (Covid-19) pathogen transmission, micro-bubble generator, as well as improved building plumbing and ventilation systems have been recommended (Al Huraimel et al., 2020; Elsamadony et al., 2021; Tran et al., 2021). Another study recommends protection of fragile water sources from industrial and anthropogenic pollution (Vallejos et al., 2015). To remove persistent emerging contaminants of public health concern from water and WW, recent studies recommend ultrasonication, membrane treatment and nanoadsorbents (Chu et al., 2017; Joseph et al., 2019; Kim et al., 2018). The emerging contaminants include EDCs, PPCPs (pharmaceuticals and personal care products) and heavy metals.

Plastics constitute 60-80% of global marine debris and is a major environmental concern because it poses threat to marine wildlife, human food chain accumulation and biomagnification (Lestari and Trihadiningrum, 2019; Raha et al., 2021; Seltenrich, 2015). The endemic global marine plastic pollution is a reflection of inadequate solid waste management on land and arose due to stormwater transport of plastic wastes from land sources into water bodies during SO. Dangers of plastic include accumulation of organic contaminants by microplastics, biofilm formation and growth, biodiversity reduction, transmission o invasive species and diseases (Beaumont et al., 2019; Compa et al., 2019; Gorman et al., 2019; Janhke et al., 2017). Besides the hazardous and non-biodegradable nature of marine plastics, plastic ingestion and entanglement of marine animals contribute to the death of thousands of marine wildlife and reproduction impairment (Desforges et al., 2018; Fossi et al., 2018; Galgani and Loiselle, 2021; Keller and Wyles, 2021). Therefore, marine plastic pollution has been identified as a planetary boundary threat to marine ecosystem and human health which may be irreversible if left unchecked (Borrelle et al., 2017; Villarubia-Gomez et al., 2018). Suggested solutions include plastic waste recovery, promotion of plastic recycling in construction and commercial products; source reduction, increased environmental awareness and mobilization of international actions towards global marine plastic governance (Alfonso et al., 2021; Fadeeva and Van Berkel, 2021; Raha et al., 2021; Sojobi et al., 2016; Sojobi and Owamah, 2014; Wilcox et al., 2016; Xanthos and Walker, 2017).

Groundwater pollution occurs through sewer exfiltration (leakage) from sewer network, infiltration from surface water and storm runoff (Gaffield et al., 2003; Mikkelsen et al., 1997; Pitt et al., 1999; Wallace et al., 2021; Wolf et al., 2012). While sewer leakage occurs due to deterioration of aged sewer/pipes infrastructure, sewer defects and poor rehabilitation (Chisala and Lerner, 2008; Chughtai and Zayed, 2008; Davies et al., 2001; Olds et al., 208; Wolf et al., 2004) , infiltration is determined by the aquifer characteristics, hydraulic loading and pipe/sewer material (Ellis, 2001; Heinz et al., 2009). With the poor state of sewer infrastructure globally (Harvey and McBean, 2014; Khan et al., 2010), pathogens can easily be transmitted into the environment leading to disease outbreaks (Chisala and Lerner, 2008; Heinz et al., 2009). Therefore, improvement in surface water quality, upgrading sewer infrastructure and ensuring regular rehabilitation of urban sewer network contribute towards groundwater protection, reduction of pathogen transmission and improved public health.

EDCs and PPCPs are emerging, toxic and hazardous contaminants with the capability of altering natural hormones thereby affecting the health of contaminated humans/wildlife (Celic et al., 2020; Farounbi and Ngqwala, 2020; Sun et al., 2013; Vieira et al., 2021). Removal of EDCs in the environment has received international attention due to the long-term health risks to humans and wildlife (Celic et al., 2020; Schug et al., 2016). The long-term consequences include impairment of neurodevelopment in children such as autism, breast and prostrate cancer, obesity and diabetes type 2, alteration of sperm quality and fertility to mention a few (Eve et al., 2020; Kasonga et al., 2021; WHO, 2014). Low public awareness, low evidence on human exposure risks, incompetent existing regulations and political responsibility makes EDC removal challenging (Wee and Aris, 2019). In addition, removal of EDCs in wastewater is difficult due to the complex structures of EDCs, inefficient removal by conventional WWT and their pervasiveness in the environment (Liu et al., 2021; Schug et al., 2016; Sun et al., 2016; Vieira et al., 2021). Discharge of SO and poorly treated wastewater effluents from WWTPs that are rich in EDCs undermine the safety of drinking water and access to safe public water supply (Wee and Aris, 2019). Therefore, biodegradation, multi-stage/combined WWT processes and advanced WWT with nanofiltration are recommended for enhanced removal or reduction of EDCs in wastewater treatment (Dai et al., 2021; Dotan et al., 2016; Kasonga et al., 2021; Vieira et al., 2021) (Vieira et al, 2021; Kasonga et al, 2021; Dotan et al, 2016; Dai et al, 2021). In addition, replacement of pesticides, herbicides and industrial chemicals in agriculture and manufacturing of pharmaceutical and personal care products with ecofriendly alternatives is also recommended to avoid dietary and lifestyle exposures to EDCs (Autrup et al., 2020; He et al., 2015; Li et al., 2021b; Meczua et al., 2012).

Policy and social interventions are necessary to reduce/eliminate infections during disease outbreaks and pandemics. Since such interventions are made by government, combination of insights from policy makers and scientists are important to come up with cost-effective interventions (Haushofer and Metcalf, 2020; Manipis et al., 2021) (Haushofer & Metcalf, 2020; Manipis et al, 2020). Recent studies revealed that aggressive social interventions were more effective in saving both human lives and the economy compared to lenient infection control measures (Silva et al., 2020; Ueda et al., 2021) (Silva et al, 2020; Ueda et al, 2021). The most effective infection control measures to suppress disease transmissions involved multiple strategies such as school and university closures, home quarantine, case isolation, enhanced personal hygiene, beach closure and social distancing before vaccination is available and distributed (Cauchemez et al., 2009; Ferguson et al., 2006; Ferguson et al., 2020; Germann et al., 2006; Jones et al., 2020a; Milanes et al., 2021) . While suppression is favourably recommended, it causes severe economic hardships which need to be mitigated (Kochanczyk and Lipniacki, 2021). Therefore, welfare policies need to be put in place to take care of the vulnerable populace such as low-income households, informal workers, slum dwellers, low-skilled workers and self employed (Aquino et al., 2020; Aum et al., 2021; Benfer et al., 2021).

Covid-19 pandemic present peculiar challenges and opportunities for solid waste management. The challenges include intensification of single-use plastics such as face masks, food containers and gloves, safety protection of waste handlers due poor waste handling, reduction of waste collection due to fear of infection, pathogen transmission during waste treatment/processing, reduction in demand for recycled waste materials and recycling of contaminated bottles (Nzediegwu and Chang, 2020; Ragazzi et al., 2020; Sarkodie and Owusu, 2021; Sharma et al., 2020; Tripathi et al., 2020; Zhou et al., 2021). The opportunities presented for efficient solid waste management include automated waste management, internet of things, automated waste separation, development of non-incineration disposal technologies, improved guidelines for waste collection, storage and treatment, regular maintenance of stormwater systems, decentralized waste management and investment in recycling technologies (Fan et al., 2021; Iyer et al., 2021; Kulkarni and Anantharama, 2020; Pasternak et al., 2021; Ragazzi et al., 2020; Sharma et al., 2020; Singh et al., 2020; Zhou et al., 2021). Therefore, solid waste management should be seen as essential public health service which should be integrated with public health emergencies (Armitage, 2007; Kulkarni and Anantharama, 2020).

Furthermore, vector transmission of pathogens poses a global threat to human health due to their presence mostly in tropical and sub-tropical regions of the world and transmission through companion and farm animals (Schorderet-Weber et al., 2017; Shaw and Catteruccia, 2019; Wimberly et al., 2020). For instance, mosquito species such as Aedes aegypti and Aedes albopictus poses threat of spreading viruses such as yellow fever, dengue, chikungunya, Zika, West Nile, Chikunguya viruses as well as encephalitis (Whiteman et al., 2019). Favourable conditions for such transmission are tree covers, micro-climatic conditions, high impervious surfaces, unmaintained drains and socio-economic conditions (Whiteman et al., 2019; Wimberly et al., 2020). In order to curb vector pathogen transmission to humans in urban and rural environments, integrated vector surveillance and pathogen prevention/intervention campaigns have been recommended alongside bio-chemical control measures, lethal traps and improved water and sanitation systems (Ferraguti et al., 2021; Kwan et al., 2017; Schorderet-Weber et al., 2017; Sharma and Lal, 2017; Shaw and Catteruccia, 2019; Singh et al., 2018; Whiteman et al., 2019). Also, optimization of combination of various intervention measures, co-ordinated development of local capacity and development of effective vaccines are also recommended to prevent vector-borne diseases (De la Fuente and Estrada-Pena, 2019; Petersen et al., 2019; Rocklov and Dubrow, 2020).

4.3 Modelling-based studies

Four modelling approaches are identified from previous studies and are summarized in Table 5. The top modelling aproach utilized is categorized under multiple techniques (63%), followed by AI approaches (19%), while the least deployed approaches are numerical and statistical modelling techniques (9% each), as shown in Figure 10 (a). Multi-techniques involve combination of different complementary techniques, as shown in Figure 10 (b). This approach has the capability to model and reveal sewer network-WWTP-receiving water spatio-temopral complex interactions. Also, multi-technique approach helps to improve both the robustness of the modelling as well as data interpretation. As shown in Figure 10 (c), stormwater management model (SWMM), developed by the United States Environmental Protection Agency (USEPA), is the most common model utilized for hydrodynamic modelling (48%). Next in popularity is InforWorks (32%) owned by Infors and Mike 21 developed by Danish Hydraulic Institute (DHI).

In addition, artificial intelligence (AI) approaches have been utilized in modelling. The AI methods include genetic algorithm (GA), monte carlo (MC), artificial neural network (ANN), support vector machine (SVM), and boosted regression, as shown in Figure 10 (d).

ANN is suitable for complex, non-linear physical systems which vary in time and space (Aziz et al., 2013) (Aziz et al, 2013). Applications of ANN include prediction of CSO depth using rainfall data and water level of CSO chamber, forecast dry weather and wet weather SO level, detection of potential SO and infiltration, automation of storage and screening devices, risk and hazard identification and mitigation and multi-objective optimization (Abbasi et al., 2021;

Abdellatif et al., 2015; Aziz et al., 2013; Darsono and Labadie, 2007; Jang et al., 2021; Mounce et al., 2014; Rathnayake, 2021; Rosin et al., 2021; Sumer et al., 2007). Disadvantages of ANN include requires accurate calibration and data pre-processing requirements, susceptible to overfitting and overtraining and lack of transparency to aid analysis and performance interpretation (Livingstone et al., 1997; Mounce et al., 2014; Rosin et al., 2021). The advantages of ANN include suitable for complex problems, adaptive learning, high execution speed and fault tolerance (Dumitru and Maria, 2013; Loke et al., 1997). Suggested methods to overcome the shortcomings of ANN and improve its accuracy include reduction/restriction of network size, limiting the magnitude of the weights applied, selection of suitable architecture and appropriate training, booststrapping and hybridization (Dreiseitl and Ohno-Machado, 2002; Dumitru and Maria, 2013; Khashei and Bijari, 2010; Livingstone et al., 1997).

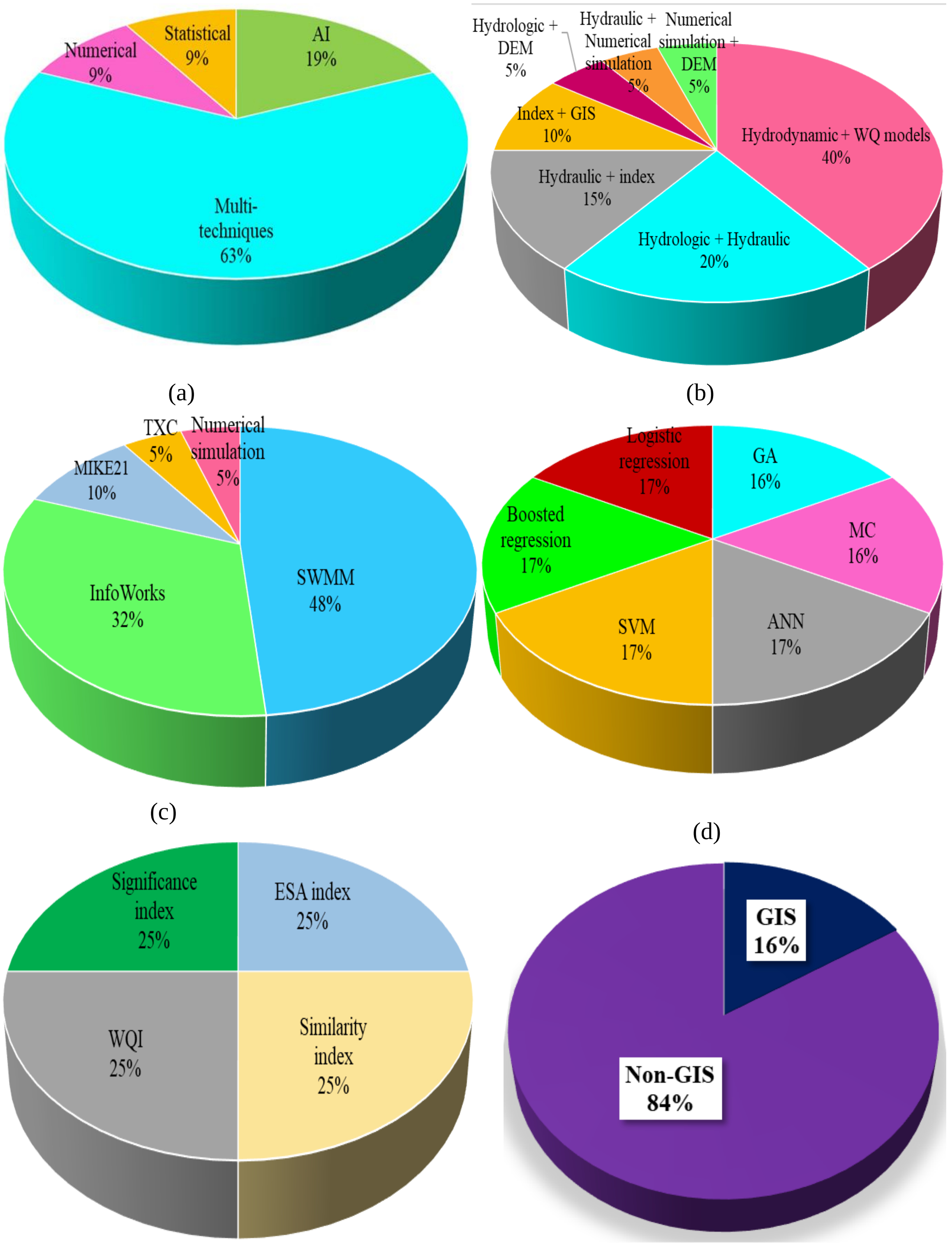
On the other hand, support vector machine (SVM) has strong adaptability, global optimization, and a good generalization performance because it include aspects and techniques from machine learning, statistics, mathematical analysis and convex optimization and has been applied in storm runoff and flood forecasting (Raghavendra and Deka, 2014). The main advantages of SVM is simultaneous reduction of model complexity and prediction error, good performance in classification and regression task (Meyer et al., 2003; Raghavendra and Deka, 2014). Also, SVM has higher classification accuracy compared to ANN, can be utilized with small data sets and high-dimensional data (Pal and Mather, 2005). Also, SVM performed than logistic regression in monitoring land use changes and has been applied flood forecasting and flood mapping when combined with GIS (Han et al., 2007; Mustafa et al., 2018; Tehrany et al., 2015). Disadvantages of SVM include may require large amount of data, time-consuming, susceptible to error from utilization of past data and difficulty in model interpretation (Cevik et al., 2015; Laouti et al., 2014; Yan et al., 2018). Recent studies reported that SVM performed better than logistic regression and ANN (Mustafa et al., 2018; Pal and Mather, 2005) .

Monte Carlo is a statistical/mathematical technique for used to predict possible outcome of output based on the distribution of the input parameters. Monte Carlo analysis can provide better information to decision makers about the potential risk of failures and alternative treatments of SO (Verhuelsdonk et al, 2021). Examples include assess risk of WWTP effluent exceeding regulatory requirements and potential savings in comprehensive plant optimization (Benedetti et al., 2006; Rousseau et al., 2001). Advantages of Monte Carlo include relatively easy to understand, assessment of the uncertainty in model output via sensitivity analysis and identification of major input factor responsible for most of the model output variability (Korving et al., 2002; Sriwastava et al., 2018; Tavakol-Davani et al., 2019; Torres-Matallana et al., 2020). Disadvantages of Monte Carlo include output accuracy depends on utilization of reasonable/fair assumptions, tendency to underestimate risk events, computational requirements, time-consuming and susceptible to overfitting (Dilks et al., 1992; Han et al., 2007; Thorndahl et al., 2008).

Genetic algorithm (GA) is an efficient algorithm/tool inspired by nature for real-time optimization of the sewer network system for effective decision making to control SO (Bonamente et al., 2020; Zimmer et al., 2015). GA has advantages of flexibility, prompt adaptation to changing conditions and reliability and limited CPU requirements (Bonamente et al., 2020). However, recent studies recommended combination of model predictive control and GA as well as GA and ANN for real-time control of urban sewer systems and to improve performance of GA and reduce network load without sacrificing quality (Petrosov et al., 2021; Rauch and Harremoes, 1999). Advantages of GA include suitable for large, complex and poorly understood problems, robust, stochastic and supports multi-objective optimization within a short computation time (Rao et al., 2008) (Rao et al, 2008). Disadvantages of GA include difficult to design and represent the problem, computationally expensive, time-consuming and premature convergence (Katoch et al., 2021).

Boosted regression is a framework that aims to reduce the bias and variance in a supervised learning technique. Its advantages include does not require data pre-processing, handles missing data, highly flexible, high predictive performance, easy implementation of complex interactions while its disadvantages include prone to overfitting, computationally expensive and its high flexibility results in multiple parameters directly affecting the model behavior (Abeare, 1999; Elith et al., 2008; Hutchinson et al., 2011). Boosted regression has been applied in predicting occurrence of chemicals of emerging concern in surface water and bottom sediment, prediction of sewer pipe sediment, flow prediction in sewer and drainage system (Hu et al., 2018; Kiesling et al., 2019; Mohammadi et al., 2020).

Logistic regression his a statistical method for predicting the outcome of a binary variable from one or more input variables. Logistic regression has been applied in predicting the influence of rainfall and imperviousness on storm overflow, predicting overflow discharges and annual number of overflow discharges, modelling the risk of SO triggered by sea level rise and design of hydraulic structures for SO (Bartosz et al., 2018; Meyers et al., 2021; Szelag et al., 2019; Szelag et al., 2020). Advantages of logistic regression include easier to implement compared to most machine learning techniques, suitable for dataset that can be linearly separated, provides additional insight on the relationship between dependent and independent variables (Thanda, 2020). The disadvantages include unsuitable for non-linear problems with complex relationships, requires fairly large dataset for improved accuracy, cannot provide continuous outcome and susceptible to overfitting.



(a) (b)

(c) (d)

(e) (f)

Figure 10 (a) Modelling-based approaches (b) Multi-technique approaches (c) Hydrodynamic modelling approaches (d) AI modelling approaches (e) Index classification approaches (f) GIS utilization

Though computationally intensive, the AI modelling approaches are suitable for modeling complex interactions of sewer network-WWTP-receiving water nexus. In addition, AI approaches are effective for carrying out multi-objective optimization problems to minimize environmental impact of SO.

Several indices that are utilized to simplify management decision making are displayed in Figure 10 (e) and are often combined with geographic information system (GIS). ESA (environmental sensitive areas) index combines several indices, which cover vegetation, climate, soil quality, and management quality (De Paola et al., 2013). Similarity index is useful for rainfall classification to identify extreme rainfall that can induce sewer overflow (SO) and their distribution pattern (Yu et al., 2013). Water quality index (WQI) is useful in portraying spatio-temporal deterioration changes in receiving waters to prioritize intervention schedule. Similarly, significance index takes into consideration population served by sewer network, available dilution, type of receiving water, and their environmental services. Though subjective, the index is useful in prioritizing SO monitoring sites and reveals areas with potential high risk of SO impact (Morgan et al., 2017). Of the assessed studies, only 16% utilize the GIS system, as shown in Figure 10 (f). This implies that there is ample opportunity to improve GIS applications in monitoring SO. GIS has been utilized to demonstrate the impact of land cover changes (Wilson et al., 2020), display environmentally sensitive areas (De Paola et al., 2013), and areas of high ecological risk (Chen et al., 2003).

Table 5. Summary of modelling-based studies

Category	Summary/Remark	References
AI modelling	AI modelling approach is used in multi-objective optimization of urban sewer systems to minimize pollution load, operational cost, cost-effective epidemiological modelling, hindcasting of past SOs, and prediction of pollution in waterways. AI has also been utilized to identify dominant factors which cause microbial pollution and biodiversity loss in waterways and their interactions. This approach is useful in hydraulic modelling and optimization of hydraulic structures.	(Medema et al., 2020; Meyers et al., 2021; Rathnayake and Anwar, 2019; Roushangar and Akhgar, 2020; Vijayashanthar et al., 2018; Walsh and Webb, 2016)
Multi-technique	Simulates impact of SO on the environment, contributions of different factors, and assesses efficiency of different intervention measures. With the aid of GIS and indices, multi-technique is useful in	(Andres-Domenech et al., 2010; Chen et al., 2003; Chen et al., 2004; De Paola et al., 2013; Fu et al., 2009; Goncalves et al., 2017; Guo et al., 2015; Li et al., 2010;

	delineating areas of different environmental risks, prioritize monitoring of SO for different pollutants, characterize rainfall patterns that contribute to SOs, and guide emergency preparedness. Studies in this category recommend optimizing WWTP efficiency, improving capacity of sewer networks, reducing density of or illicit sewer connections, and proper placement of SO outfall.	Morales et al., 2017; Morgan et al., 2017; Quijano et al., 2017; Reyes-Silva et al., 2020; Semadeni-Davies et al., 2020; Taghipour et al., 2019; Tolouei et al., 2019; Wei et al., 2019; Wilson et al., 2020; Yu et al., 2013; Zhang and Guo, 2015; Zhu et al., 2017)
Numerical	Numerical approach utilizes multi-objective optimization of treatment of WW in terms of CO_2 emission and cost-benefit, multi-media modelling of chemical contaminants, and prediction of water level during and after water spill during SO.	(Al Ketife et al., 2019; Cohen and Cooter, 2002; Tian et al., 2017)
Statistical	Statistical approach elucidates rainfall and non-rainfall factors responsible for SOs. It is utilized for quality assessment and classification of coastal waters in terms of risk, and it reveals frequency of contamination. Studies in this group recommend control of new developments, provision of sewage/solid waste disposal systems, pre-screening and WWTP treatment of SO to avoid pollution and mitigate risks to tourists and residents. Estimated loss of US$ 25 billion dollars has been reported in the Caribbean due to pollution	(Abdul azis et al., 2018; Mailhot et al., 2015; Soriano and Rubio, 2019)

4.4 Hybrid method-based studies

Studies reporting hybrid modelling are summarized in Table 6. The hybrid modelling approach combines field sampling/laboratory studies with modelling techniques, which include hydrodynamic, numerical, ANN or statistical, as shown in Figure 11 (a) and (b). Various types of analyses carried out in the field sampling part are shown in Figure 1 (a). It is observed that more attention has been paid to both physical and physico-chemical analyses than biological and microbiological analyses. More attention is required to showcase the impact of organic pollution (from physico-chemical pollutants) on aquatic organisms. In addition, more research is needed to show the microbiological impact of virus and bacteria that are transported to the receiving waters during SO.

The four modelling approaches that have been employed under the hybrid method are shown in Figure 11 (b). Most of the studies (53%) utilize hydrodynamic models, followed by numerical modelling, while the least employed methods are ANN modelling (8%) and statistical modelling (8%). Hybrid method displays spatial-temporal contaminant transport and simulate impact of urban effluent/SOs on receiving waters. It is also useful in evaluating different (SO) management strategies to select the best design and management option to mitigate the impact of SO on aquatic organisms (e.g. fishes). It can also be used to reduce public health risks to end users who use such rivers and beaches for recreation and sources of drinking water.

To mitigate biodegradation caused by sewer overflow, a recent study suggests combined application of sedimentation tank and multi-stage treatment with plants (Jin et al., 2020). Based on this combined set-up, the authors achieved TP (total phosphorus) and COD (chemical oxygen demand) removal of 23.9% and 45.9%, respectively during SO event. With the aid of GIS, a recent research maps out a study area and finds that seven lakes out of nine are unsuitable for fishes in terms of BOD and DO. Pollution in those lakes is attributed to anthropogenic pollution from agricultural activities, fish farming, and poor domestic waste disposal (Khwairakpam et al., 2020). Groundwater infiltration, through joints and sewer leakage, has also been reported to affect WWTP efficiency. A field study shows that SO events can also result from low delivery capacity and blockage of branch sewer pipes (Yang et al., 2021a).

In order to diagnose and mitigate SO impact on the environment, a recent study recommends a sewer system-treatment plant-receiving natural environment approach (Todeschini et al., 2011). Also, the low treatment efficiency and poor cost-effectiveness of WWTP are due to a lack of optimization of the various processes of WWTP (Xu et al., 2020). Therefore, CFD (computational fluid dynamic) modelling of the WWTP processes is encouraged before constructing future WWTPs to improve treatment efficiency, avoid redesigning costs, and reduce dredging/maintenance costs.

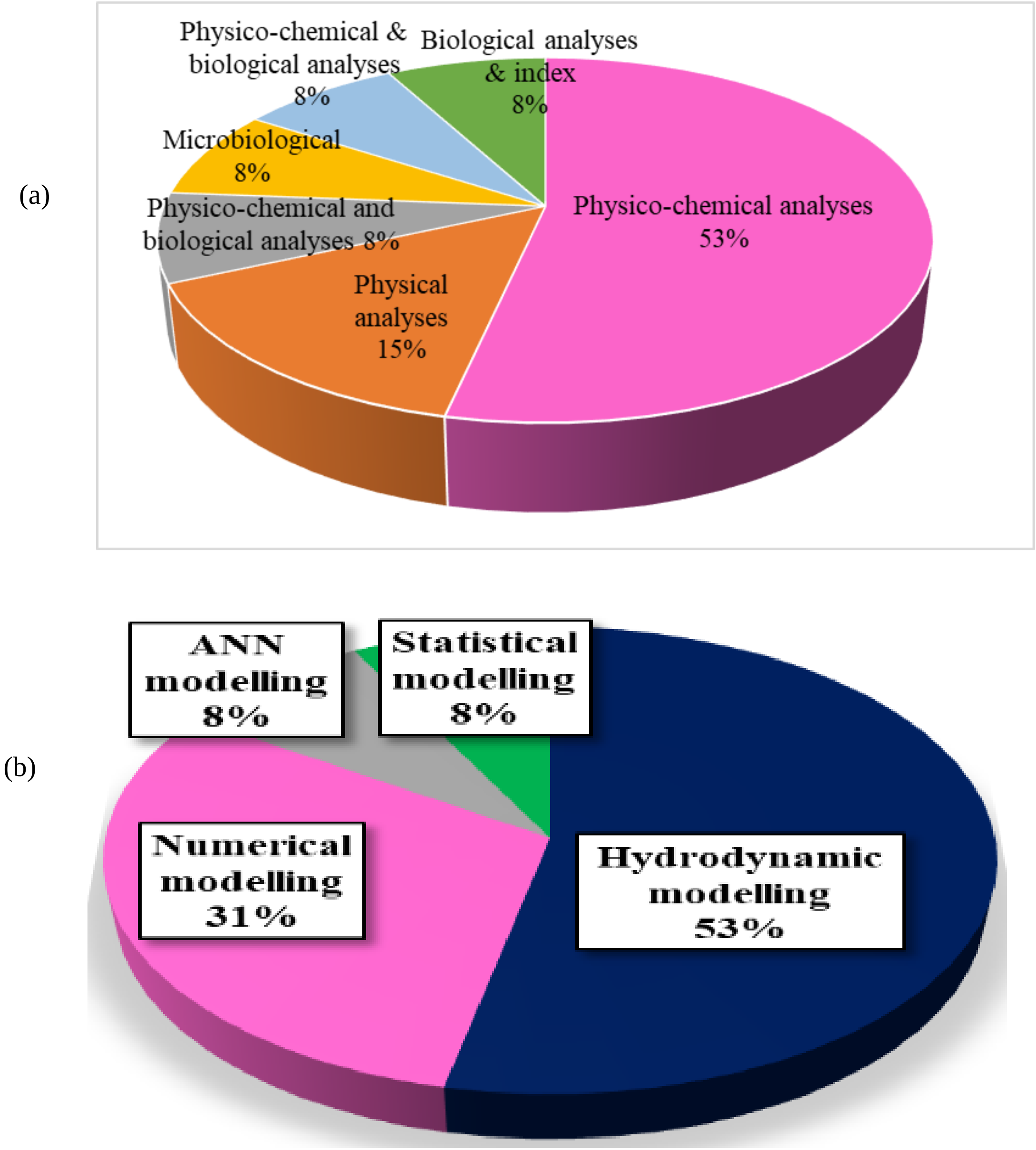


Figure 11. (a) Distribution of types of field/laboratory analyses (b) Modelling approaches for hybrid method

Table 6. Summary of hybrid method-based studies

Category	Summary/Remark	References
Physico-chemical	SO causes permanent short and long-term impacts on rivers, such as oxygen depletion, increased BOD, and turbidity, which affect the suitability of those habitats for fishes and other aquatic lives. DO impact is caused by the degradation of organic matter by heterotrophic bacteria and reduced phytoplankton activity. 30-70% of the impacts can be reduced with different mitigation strategies. ANN and SWMM can accurately predict water quality in sewers and stormwater systems.	(Even et al., 2007; Jin et al., 2020; Khwairakpam et al., 2020; Riechel et al., 2016; Tiwari and Sihag, 2020; Xu et al., 2017; Yang et al., 2021a)
Physico-chemical & microbiological	Organic loading and sediment resuspension from SO cause serious chemical and biological degradation of river and beach water quality, thus reducing aquatic biodiversity. Major contaminants include COD, BOD_5 and *E. coli*. Besides, *E. coli* 500 times over the regulation threshold has been observed during SO. Mitigations studies recommend microbial pollution monitoring at beaches and repositioning marine outfalls.	(Kim et al., 2018; Todeschini et al., 2011)
Physical analysis	This approach recommends optimizing the design of various processes of WWTP to improve WWT efficiency and hence, minimize residence time and dredging costs.	(Xu et al., 2020)
Microbiological analysis	This technique recommends source-water protection against SO impacts on public health. Highest *E. coli* concentration has been found in drinking water during SO events.	(Jalliffier-Verne et al., 2016)
Biological & Index	This method recommends estuarine fish assessment index to monitor the impact of different environmental stressors on fishes.	(Cabral et al., 2012)
Physico-biological	Urban, industrial, and agricultural activities serve as important sources of chemical pollutants and nutrients, which cause oxidative stress with genotoxic effects in aquatic organisms. The pollutants include PCB, PAH, herbicides, personal care products, pharmaceuticals, and trace metals. Protection of watercourses from these toxic pollutants is crucial to protect aquatic organisms and public health.	(Stefani et al., 2018)

4.5 Studies based on laboratory/field experiments

Studies focusing solely on laboratory/field experiments only are displayed in Table 7. The research focus distribution of studies concentrating on only laboratory experiments is also displayed in Figure 12. Almost half of the studies focuses on degradation and settling treatments of wastewater. Both adsorption and degradation techniques are focused on the elimination of emerging contaminants/micropollutants, such as acetaminophen, naproxen, trinizadole, and benzotriazole (Jung et al., 2015; Lee et al., 2019; Velo-Gala et al., 2017). These contaminants are difficult to remove using conventional wastewater treatment protocols. Activated biochar and UV, solar radiation, and chlorination have been utilized to remove them at different removal efficiency of between 50 and 100%. Furthermore, settling methods exploit polyacrylamide and sand to remove iron nanoparticles and suspended solids. Polyacrylamide is a cost-effective method for improving WWTP effluent through the removal of iron nanoparticles by dynamic gravity settling (Wang et al., 2015). The dynamic gravity process is compatible with conventional WWTP process.

A recent study also reports that suspended solids in wastewater can be removed faster (< 4 s) by dosing with ballasted sand (Zafisah et al., 2020). Turbidity removal efficiency of 90% has been achieved at 2 mg/L of flocculants to 1 g/L of sand. Future studies should investigate the best combination of sand and flocculants and application intervals to improve the efficiency of ballasted flocculation method. It is also observed that different filtration membranes require different design criteria, operation, and maintenance to achieve similar performances (Muthukumaran et al., 2011). In order to improve the longevity and efficiency of filtration membranes, pretreatment of wastewater is required to reduce membrane fouling caused by pore blockage and cake formation.

Some studies have also focused on sediment transport study by examining sediment erosion and deposition in sewer pipe. Sediments and biofilms have been reported to play crucial roles in the biodegradation processes taking place in sewer networks (Regueiro-Picallo et al., 2020). Therefore, screening out the sediments from entering the sewer network and regular flushing maintenance are required to improve WWTP efficiency. Such practices will reduce both sediments and biofilms in sewer networks and significantly reduce microbial and organic pollution of receiving downstream waters during SO. Co-digestion of WWTP sludge with food waste at elevated temperature of 50 ^{o}C has also been recommended to reduce the viability of Covid-19 in WWTP sludge by up to 99.7% (Bardi and Oliaee, 2021). Such high efficiency is attributed to the synergistic effects of volatile fatty acid (VFA) accumulation, long operation condition (45 hours), and temperature.

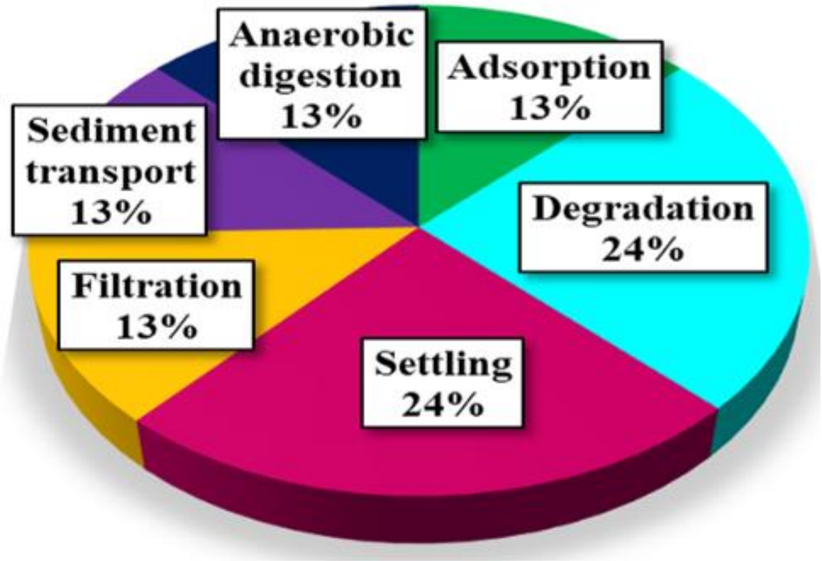


Figure 12. Research focus distribution of studies focusing on laboratory experiments

Studies focusing on field experiment are also displayed in Table 7. It is observed that rain gardens can be used to dissipate urban storm runoffs and 50% dissipation can be achieved within two days (Nemirovsky et al., 2015). Rain gardens are green infrastructure which promote infiltration of storm runoffs into the groundwater, evapotranspiration, and capture of stormwater for reuse. The system requires construction of several wells. The efficiency of the rain garden is determined by the infiltration capacity of the soil, the surface area of the rain garden, and the number of connections to the rain garden. The optimal number of rain gardens depends on the type of drainage areas and SO control targets (Shamsi, 2012). Rain gardens with between 10 to 20% of impervious surface area are recommended and are cost-effective alternative to the large-scale centralized stormwater sewers and detention tunnels (Aad et al., 2010; Dussaillant et al., 2004).

Benefits of rain gardens include 38% total runoff volume reduction, 33% peak reduction and 76% stormwater reduction (Aad et al., 2010; Alyaseri et al., 2017). Another study reports draining time of 1.5 mins to 8 hours with an average drain time of 1.3 hours (Asleson et al., 2009). Another study shows runoff reduction of 12.7% - 19.4%, volume reduction of 13 - 62%, and peak flow reduction of 7 - 56% depending on the SO event (Autixier et al., 2014). Beside peak flow reduction and delay in peak flow arrival time, rain gardens are useful in pollution reduction through natural attenuation of contaminants during infiltration (Li et al., 2016; Pennino et al., 2016). However, the major drawbacks of rain gardens are unsuitability for large runoff events and costly maintenance requirements (Alyaseri et al., 2017; Autixier et al., 2014). Owing to overlapping of jurisdictional boundaries in conservation and disposal of SO, public buy-ins, institutional co-operation, and appropriate location are required (Chaffin et al., 2016). Potential cost savings of US$ 35 million over a 50-year period has been reported for combined green/gray infrastructure (Cohen et al., 2012). Therefore, future studies are required to assess and design cost-effective rain gardens.

Table 7 Summary of studies based solely on laboratory and field experiments only

Category	Summary	References
	Laboratory experiments	
Adsorption	Activated biochar removes 94.1% and 97.7% of acetaminophen and naproxen, respectively through adsorption. Therefore, optimized combination of adsorption and other methods, such as coagulation, is recommended.	(Jung et al., 2015)
Degradation	Recommends photo-Fenton systems comprising UVC and solar radiation for removal of antibiotics from contaminated water and wastewater. Also, UV-A/chlorination process is recommended for effective removal of emerging contaminants in WWTPs and reduction of their toxicity.	(Lee et al., 2019; Velo-Gala et al., 2017)
Settling	Recommends dynamic gravity settling with polyacrylamide and ballasted settling with sand for fast and efficient wastewater treatment for removal of nanoparticles and suspended solids from coagulation/flocculation process	(Wang et al., 2015; Zafisah et al., 2020)
Filtration	Proposes the use of either tubular or spiral membranes to improve wastewater treatment. While tubular has a very high removal of turbidity, COD, and colour, it requires pre-treatment owing to its high fouling resistance and low permeates. On the other hand, spiral membrane has a lower COD and colour removal and requires additional treatment for colour removal.	(Muthukumaran et al., 2011)
Sediment transport	Flume test is utilized to study in-sewer sediments deposition, erosion and transport. The test reveals sediment deposition cohesion during long dry weather and biodegradation of sediments due to their organic content, which improves sediment bed resistance. Test also shows that 74% of pollutants attached to sediments decrease to 56%, while 75% of the pollutants attached to biofilms remains constant. Screening-out sediments from wastewater before entering the sewers is recommended to reduce biodegradation of sewers, organic load transmission, and improve WWTP efficiency.	(Regueiro-Picallo et al., 2020)

Anaerobic digestion	Proposes anaerobic co-digestion of food waste (FW) and Covid-19 infected sewage sludge (SS) to eliminate Covid-19 to undetectable levels. Combined control of operational temperature and organic loading (OL) is crucial to eliminate Covid-19. At 20 °C + OL of 3.5 gVS/L, 35 °C + OL of 3.5 gVS/L and 50 °C + OL of 1.5 gVS/L, Covid-19 RNA is not detected.	(Bardi and Oliaee, 2021)
Field experiment		
Rain garden	Recommends vegetated rain gardens for stormwater control.	(Nemirovsky et al., 2015)

5. Sewer overflow impact on public health

Sewer overflow negatively influences drinking water, surface waters and recreational beaches, groundwater, and irrigated foods as shown in Table 10. Consumption of such infected foods/water and direct contact with infected foods/water and animals have facilitated disease outbreaks in several countries (Campos and Lees, 2014; Caplin et al., 2008; Elmahdy et al., 2019; Farkas et al., 2018; Han and He, 2021; Hassard et al., 2017; Lee et al., 2012; O'Reilly et al., 2007). The gastrointestinal outbreak on South Bass Island, which affected both residents and tourists, was caused by consumption of contaminated drinking water sourced from fecally-contaminated public and private wells (O'Reilly et al., 2007). Reported symptoms of infected patients include diarrhea, abdominal cramps, nausea, vomiting, fever and bloody diarrhea and were attributed to fecal-indicator pathogens such as *Arcobacter, E.coli, C. Jejuni, Salmonella. Giardia spps*. found during investigations (O'Reilly et al., 2007). Both environmental and epidemiological investigations linked the contamination to disposal of untreated sewage and infiltration of contaminants from septic tanks through the fragile karst aquifer (O'Reilly et al., 2007).

Furthermore, another study reported that highly contaminated beaches pose health risk to beachgoers (Lee et al., 2012). The most prevalent pathogen found in Lake Erie beach water namely *Arcobacter spp* was significantly correlated with human bacteroides (*Prevotella*), which is a fecal contamination marker. Fecal and microbial contamination of the beach was attributed to a large population of birds bathing in the beach waters and sanitary/sewer overflows and the contamination is often high during the swimming season (Lee et al., 2012). Likewise, another study reported outbreak of gastroenteritis in children which was linked to fecal-oral transmission of human adenovirus via contaminated water and food (HAdV) (Elmahdy et al., 2019). The inadequate removal of HAdV in treated effluents at the WWTP facilitates release of pathogens into the water environment and utilization of such water for irrigation, shellfish cultivation and any industrial process engender pathogen transmission (Elmahdy et al., 2019; Katayama et al., 2002).

Food-chain transmission of pathogens was confirmed in gastrointestinal outbreaks caused by norovirus in some studies and was attributed to consumption of fish, shellfish and oysters harvested from sewage-polluted rivers and estuarine waters (Campos and Lees, 2014; Farkas et al., 2018; Hassard et al., 2017). In addition, epidemic outbreak of antibiotic-resistant enterococci was linked to food-chain transmission via infected dairy cattle, sheep and poultry (Caplin et al., 2008). A recent study also reported that communities served by combined sewer systems are prone to higher risks of Covid-19 transmission due to their frequent exposure to sewer overflow which contains infected human urine and faeces (Han and He, 2021). These results imply pathogen transmission occur via several routes.

Therefore, multi-barrier approach is required to protect public health and prevent pathogen transmission. In summary, pathogenic persistence and transmission is highly dependent on water and wastewater infrastructure, agricultural practices, health infrastructure, environmental surveillance, and public awareness. The public health impact is enormous when adequate attention is not given to these crucial factors.

Table 10. Public health impact of sewer overflow

Reference	Pathogens	Causes	Diseases	Locations
(O'Reilly et al., 2007)	Multi-pathogens (*Arcobacter, E.coli, C. Jejuni, Salmonella. Giardia spps.*)	Drinking sewage-contaminated groundwater	Outbreak of gastrointestinal diseases (1450 persons infected)	South Bass Island
(Lee et al., 2012)	*Arcobacter sp.*	Swimming in contaminated beach waters	Gastrointestinal diseases	Lake Erie beach, Ohio
(Osuolale and Okoh, 2015)	Human hepatitis A Virus (HAdV)	Discharge of poorly-treated WW effluent	Inflamed liver, fever, dark urine, jaundice	Eastern Cape, South Africa
(Elmahdy et al., 2019)	Human Adenovirus (HAdV)	Disposal of poorly treated WW & sewage sludge	Outbreak of grastroenteritis in children (60 children)	Egypt
(Campos and Lees, 2014)	Norovirus (NoV)	Consumption of shellfish harvested from sewage-polluted estuarine waters	Epidemic gastroenteritis	UK
(Hassard et al., 2017)	Norovirus (NoV)	Person-person contact & consumption of infected fish, shellfish & oysters	Gastrointestinal outbreaks in restaurants, etc.	Australia, USA, Netherlands, France, UK
(Farkas et al., 2018)	Norovirus (NoVGI)	Consumption of shellfish harvested from sewage-polluted rivers	Gastroenteritis outbreak (36 persons infected)	North Wales

(Han and He, 2021)	Covid-19	Sewer overflow of untreated wastewater or sewage	Community outbreak of Covid-19	USA & China
(Caplin et al., 2008)	Enterococci	Food chain transmission via infected dairy cattle, sheep and poultry	Epidemic outbreak of antibiotic-resistant enterococci	UK, Netherlands, USA & Australia

6 Health risk assessment of wastewater treatment plant

Quantitative microbial risk assessment (QMRA) is a tool for evaluating and quantifying exposure risks to pathogens, communicate associated health risks and facilitate risk management (Beaudequin et al., 2015; USEPA, 1989; Whelan et al., 2014; Yan et al., 2021) . The health risks associated with Covid-19 and various pathogens in WWTP are shown in Table 11. The reported health risks range from 0.0003-8.01. The highest health risk was recorded for children and the least risk was recorded for male adults and the total health risks is higher than reported risks from various studies since several pathogens such as bacteria, virus and protozoans are present in wastewater (Li et al., 2021a; Rodrigues et al., 2016; Yang et al., 2019b) . Therefore, children must have restricted access to WWTP. Children are the most vulnerable to pathogen exposure due to their lower rate of immunity and higher ingestion rate (De Man et al., 2014; Wade et al., 2008). The health risks arise from exposure activities such as splashing, accidental ingestion, hand-to-mouth, fomite and dermal contacts, inhalation of bioaerosols and skin contacts (Dada and Gyawali, 2021; Gholipour et al., 2021; Li et al., 2021a; Mbanga et al., 2020; Pasalari et al., 2019; Yan et al., 2021; Yang et al., 2019a; Yang et al., 2019b; Zaneti et al., 2021). For Covid-19, the daily health risks of WWTP workers was 5.5-23.6 times higher than annual tolerable risk of 0.00055 (Zaneti et al., 2021) . This implies Covid-19 poses serious occupational hazard to WWTP workers. Besides Covid-19, several health risks are also posed by other pathogens such as enterobacteria, staphylococcus, pseudomonas, rotavirus, norovirus and E.coli found in wastewater at the WWTP and surrounding environment (Li et al., 2021a; Mbanga et al., 2020; Pasalari et al., 2019; Yan et al., 2021; Yang et al., 2019a). The main risk of infection for WWTP workers are aerosolization of pathogens during pretreatments of wastewater/sewage, operation of aerobic moving bed biofilm reactor, aeration units and sludge dehydration and treatments (Carducci et al., 2018; Sanchez-Monedero et al., 2008; Yan et al., 2021; Yang et al., 2021b).

In addition, significant health risks is posed to surrounding communities where the WWTP is located and was higher than the tolerable health risks of 0.0001 (USEPA, 1989) (USEPA, 1989) by 40-2500 times for norovirus and 2.2 -2300 for rotavirus, 1-10,000 for E.coli and 3600 for bacteria. This implies residents leaving close to WWTPs were at risk of exposure to aerosolized pathogens similar to WWTP workers and the disease burden depends on the dose, disease burden per case and viral concentration (Pasalari et al., 2019) (Pasalari et al, 2019). Therefore, WWTP should be located far away from residential apartments to reduce infection risks to the local communities via inhalation of bioaerosols. While generation of bioaerosols is influenced by aeration rate, source and concentration of pathogens in the wastewater and type of diffuser utilized, the distribution of the bioaerosols is determined by wind speed, relative humidity, scale of the WWTP, total suspended particulates, temperature and solar illumination (Carducci et al., 2018; Sanchez-Monedero et al., 2008; Wang et al., 2018; Yang et al., 2019a).

Table 11. Health risk assessment of various pathogens in WWTP

Pathogens	Annual risk of infection	Source of contamination	Exposure location/activities	Reference
Covid-19	0.0001-0.013*	Working in WWTP	Splashing, ingestion, Hand-to-mouth and fomite contacts	(Zaneti et al., 2021)
Covid-19	0.011-0.023	Working in WWTP	Inhalation of bioaerosols	(Gholipour et al., 2021)
Covid-19	0.0003-0.03	Working in WWTP	Inhalation of bioaerosols	(Dada and Gyawali, 2021)
Enterobacteria, Staphylococcus, Pseudomonas	1.90-2.09	Working in WWTP	Inhalation, dermal contact	(Yang et al., 2019a)
Integrated bacteria	6.85 (adults)	Working in WWTP	Inhalation	(Yang et al., 2019b)
	8.01 (children)	Around or within WWTP		
Staphylococcus	0.0002-0.064	Working in WWTP	Inhalation of bioaerosols	(Yan et al., 2021)
Rotavirus	0.00525-0.5	Working in WWTP	Inhalation of bioaerosols	(Pasalari et al., 2019)
	0.00022-0.23	Living 300-1000 m from WWTP		
Norovirus	0.177-0.5	Working in WWTP		
	0.004-0.25	Living 300-1000 m from WWTP		

E.coli	0.012-1	Working in WWTP	Accidental ingestion	(Mbanga et al., 2020)
E.coli	0.011-0.016	Working in WWTP	Bioaerosol ingestion	(Chen et al., 2021b)
S.Aureus	0.0005-0.025	Working in WWTP		
Bacteria	0.36 (children), 0.089 (male adult), 0.077 (female adult)	Living close to WWTP	Inhalation and skin contact	(Li et al., 2021a)

* probability of risk of infection for a single event

To reduce the risks, several studies have recommended several measures. Recent studies reported that infection risk and disease burden can be reduced by 86.1-100% through the use of personal protective equipment (PPEs) and training while bioaerosol generation can be reduced by > 60% through installation of UV (ultraviolet lamp) and air diffusers (Li et al., 2021a; Munoz-Palazon et al., 2021; Yan et al., 2021). In support of the use of PPE, a recent study reported significant risk reduction of 97.6% for E.coli and 97.96% for S. Aureus and significant reduction of disease burden by 97.32 % for E.coli and 97.47% for S. Aureus (Chen et al., 2021b).

Though no link has been established between Covid-19 shedding in WW and risk of infection, the risk of infection has been reported to decrease with treatment and the highest exposure risk is untreated feces and untreated sludge (Brisolara et al., 2021). Also, a recent study reported that fecal aerosols transmission of Covid-19 via wastewater through building plumbings is possible and lower than person-to-person transmission via respiratory droplets/aerosols (Ahmed et al., 2021). However, several studies have reported infection risks from Covid-19 and several pathogens during sewer overflow (Ahmed et al., 2021; Andersen et al., 2015; Boehm et al., 2015; De Man et al., 2014; Donovan et al., 2008; Duizer et al., 2016; Eregno et al., 2016; Mahlknecht et al., 2021; Morales, 2020; Rodrigues et al., 2016; Shi et al., 2021; Soller et al., 2017; Ten Veldhuis et al., 2010) as shown in Table 12. The health risk exposure occurred during bathing/swimming in beaches/recreational waters, swimming/playing in urban flood waters and sewage-impacted estuarine water, cleaning of SO floodwater from residences, food-bioaccumulation and inhalation of bioaerosols during flushing and from faulty drainages in residential apartments (Ahmed et al., 2021; Mahlknecht et al., 2021; Shi et al., 2021; Ten Veldhuis et al., 2010). Potential for aerosolization of pathogens is increased when untreated wastewater and stormwater is released during heavy rains, thereby transporting the pathogens to downstreams and upstream communities.

Table 12. Health risk assessment for contact with different pathogens during SO

Pathogens	Annual risk of infection	Source of contamination	Exposure location/activities	Reference
Cryptosporidium	5 x 10-6 – 0.004	Urban flooding of streets/roads by SO	Pedestrian and playing child	(Ten Veldhuis et al., 2010)
Giardia	0.001-0.03			
Campylobacter	0.02-0.3			
Fecal Streptococcus	0.14-0.68	Release of untreated SO into river	Beach recreation and visitors	(Donovan et al., 2008)
Enterococcus	0.14-0.67			
Norovirus	0.024-0.23		Beach surfing	(Soller et al., 2017)
E.coli	0.007-0.1	Release of partially treated sewage into ocean	Bathing in sewage-impacted recreational beaches	(Rodrigues et al., 2016)
Norovirus	0.159-0.206*	Release of untreated sewage and sewer leakage	Bathing in recreational beaches	(Eregno et al., 2016)
Campylobacter	0.84-68	Contaminated storm sewer with sewage	Swimming/playing in urban flood waters	(De Man et al., 2014)
Cryptosporidium	0.00007-0.12			
Giardia	0.0014-0.04			
Norovirus	15-52			
Enterovirus	1-24			
Enterococcus & PMMoV	0.01-0.1	Release of diluted sewage due to infiltration of stormwater into sewers	Swimming in sewage-impacted estuarine water	(Ahmed et al., 2020c)
Poliovirus	1.4 x 10-9 - 0.86*	Release of diluted poliovirus-infected wastewater	Swimming in infected water bodies	(Duizer et al., 2016)
Norovirus	0.004-0.03	Release of raw sewage	Swimming in recreational waters	(Boehm et al., 2015)

PMMoV	0.0005-1	Soil contamination during SO	Soil ingestion during outdoor recreation	(Morales, 2020)
Campylobacter	0.015-0.016	SO from overloaded sewers	Cleaning of SO floodwater from residences	(Andersen et al., 2015)
Covid-19	1×10^{-7}-5.2×10^{-5}	Swimming in infected rivers	Ingestion	(Mahlknecht et al., 2021)
	1×10^{-7}- 1.7×10^{-5}	Fishing	Ingestion during fishing & fish consumption	
	0.0015	Shallow aquifer	Ingestion	
Covid-19	1.11×10^{-10} - 0.00058	Toilet flushing	Inhalation of indoor bioaerosols	(Shi et al., 2021)
	3.53×10^{-11}	Faulty drainage		

* probability of risk of infection for a single event

Microbial risks increases during sewer overflow and children and pedestrians have 3-10 times more microbial risks than swimmers due to higher dosage of pathogens from different sources during heavy rains (Stapleton et al., 2011; Sterk et al., 2008). Illness rate of 24-226 gastrointestinal illness per 1000 have been reported for norovirus during beach surfing after SO (Soller et al., 2017). The elevated concentrations of enterovirus, norovirus, Campylobacter in both groundwater and beach water is due to the release of untreated SO and inadequately treated WWTP effluent (Schijven et al., 2015). SO also occurs due to septic fecal leaching which contaminates drinking water well and recreational waters and a recent study reported norovirus outbreak which affected 179 individuals (Mattioli et al., 2021).

Recent study reported that flooding constitute highest risk for disease burden through export of pathogen to downstream communities (Foster et al., 2021) and constitute an annual risk of 8% which is expected to increase with increased urban flooding due to heavy rain caused by climate change (De Man et al., 2014). Covid-19 RNA has been found in 21.4-81% in feces of Covid-19 cases and removal of the virus load depends on the treatment system adopted by the WWTP (Bao and Canh, 2021) . While tertiary system achieve 100% complete removal, secondary treatment has residual content of 5.4 log 10 copies/L (Randazzo et al., 2020; Wurtzer et al., 2021). However, Covid-19 transmission by aerosols via faulty sewage pipelines and inadequate ventilation systems have been reported in literature (Hwang et al., 2021)(.

Some studies reported that reduction of pathogen concentration in effluents discharged from WWTP and abatement of sewer overflow frequency is more effective in significantly reducing infection risk compared to increasing WWTP/sewer system capacity and restricting access to waterways/beaches (Goulding, 2011; Goulding et al., 2012). Therefore, mitigating pathogen transmission from WWTP during SO is important for meeting UN sustainable development goal (SDG) of safely managed water and sanitation (Mraz et al., 2021). Also, the use of multiple pathogens rather than few indicator micro-organisms is more helpful to ensure safe disposal of SO considering their significantly higher risk of infections compared to indicator micro-organisms (Mraz et al., 2021).

7. Research gaps and future research directions

The identified research gaps along with the respective future research directions are shown in Figure 13. Though significant efforts have been made to understand the impact of SO on public health, there are still rooms for improvement. The research gaps identified are highlighed below.

There is lack of standardized protocols for detecting, quantifying and inactivating microbial pathogens of bacteria, virus, phages, etc to facilitate comparison. This concern has been reported by several researchers (Ahmed et al., 2020a; Arora et al., 2020; Haramoto et al., 2020; Kitamura et al., 2021). Utilization of different procedures and experimental conditions make data comparison and benchmarking difficult. In addition, cost-effective inactivation mechanisms in different media are required (Ihsanullah et al., 2021; Kitajima et al., 2020). Also, there is insufficient studies on the impact of WASH (water, sanitation and hygiene) and POUT (point-of-use water treatment) at household and community levels in combating pathogen transmission especially Covid-19. This concern was addressed in a recent study (Sunkari et al., 2021). With the present global Covid-19 pandemic, there is need to demonstrate the potential benefits of these methods to encourage wide public acceptance at the household and community levels. In addition, their implementation should be encouraged to drive disease prevention, which is always better and cheaper than procuring a cure.

There is inadequate studies on bioaerosol and fecal-oral transmission and infectivity of pathogens in diverse environments and cost-effective disinfection/prevention mechanisms. This gap is mentioned in some recent studies (Collivignarelli et al., 2020; Dharma et al., 2021; Ihsanullah et al., 2021; Kitajima et al., 2020). Awareness and mitigation of fecal-oral and aerosolized transmission routes will safeguard residential buildings, schools, public buildings, office buildings, and commercial buildings. Timely implementation of these mechanisms will fast-track our return to normal/near-normal life post covid-19.

Also, lack of cost-effective optimization of water and wastewater treatment and sludge disposal has been highlighted in some studies (Eganhouse and Sherblom, 2001; Ji et al., 2021; Kumar et al., 2020a; Mohapatra et al., 2021; Ryu et al., 2014; Zafisah et al., 2020). Cost-effective optimization of water and wastewater treatment as well as sludge disposal is crucial to reduce operational costs and time, improve efficiency of WWTPs, and increase resilience to pathogen transmission. Also, there is lack of multi-objective optimization of sewer network maintenance to minimize sediments, pollution load, and pathogen transmission. This concern has been raised in a recent study (Rathnayake and Anwar, 2019). Sewer network maitenance is crucial to reduce environmental pollution/transmission during SO event. Inadequate water quality modelling and real-time monitoring of SO-sewer-WWTP-receiving water continuum and lack of quantified impacts and contributions from runoff, WW, and in-sewer processes. The importance of water quality modelling has been highlighted in some studies (Crocetti et al., 2020; Gasperi et al., 2010). Also, the importance of real-time monitoring has been emphasized in a recent study (Lesimple et al., 2020). Likewise, lack of comprehensive surveillance of WW, irrigation, public tap water, surface waters, and irrigated and non-irrigated foods was noted. While importance of WW surveillance has been highlighted in several studies (Mandal et al., 2020; Medema et al., 2020; Saawarn and Hait, 2021), surveillance of other transmission media are also required.

Likewise, inadequate health risk assessments of different pathogens via different transmission routes including aerolized pathogens was also observed. The importance of health risk assessment has been reiterated in several studies (Cohen and Cooter, 2002; Jeon et al., 2017; Ortega et al., 2009; Siddiqee et al., 2020). Health risk assessment is important to establish the range and occurrence of contamination and infections, and adopt appropriate mitigative measures to protect public health. Results from health risk assessments will guide appropriate policy making to reduce pathogen transmission. Also, lack of well-informed targeted, impartful policy, and social interventions to reduce pathogen transmission, safeguard public health, and improve public welfare was also noted. This concern has been highlighted in few recent studies (Adelodun et al., 2020; Sunkari et al., 2021). Proactive policies and social interventions are crucial in curbing pandemic and more scientific studies are required to provide/guide effective evidence-based policy interventions to minimize pandemics. In addition, appropriate welfare mechanisms are required to minimize the negative effects of such policy and social interventions on the low-income households.

Likewise, this study revealed inadequate studies on bioaccumulation of pathogens and chemical pollutants in edible aquatic organisms as well as food chain transmision of pathogens and chemical pollutants in irrigated foods. Some disease outbreaks have been attributed to ready-to-eat foods such as salads (van Asselt et al., 2020). In addition, there is inadequate studies to effecively mitigate plastic and litter pollution of beaches and surface waters during SO. This environmental challenge has been highlighted in recent studies (Acosta-Coley et al., 2019; Garces-Ordonez et al., 2020a; O'Briain et al., 2020). Mitigating plastic pollution is important to avoid food-chain transmission of microplastics to humans through ingestion of fish. Furthermore, there is limited studies on effective utilization of rain gardens to reduce storm runoff to sewer networks during SO event. Limited studies have shown the benefits of green infrastructure, such as rain gardens in storm runoff and pollution reduction (Aad et al., 2010; Autixier et al., 2014; Nemirovsky et al., 2015; Pennino et al., 2016; Shamsi, 2012). However, their practical application in urban environments is limited.

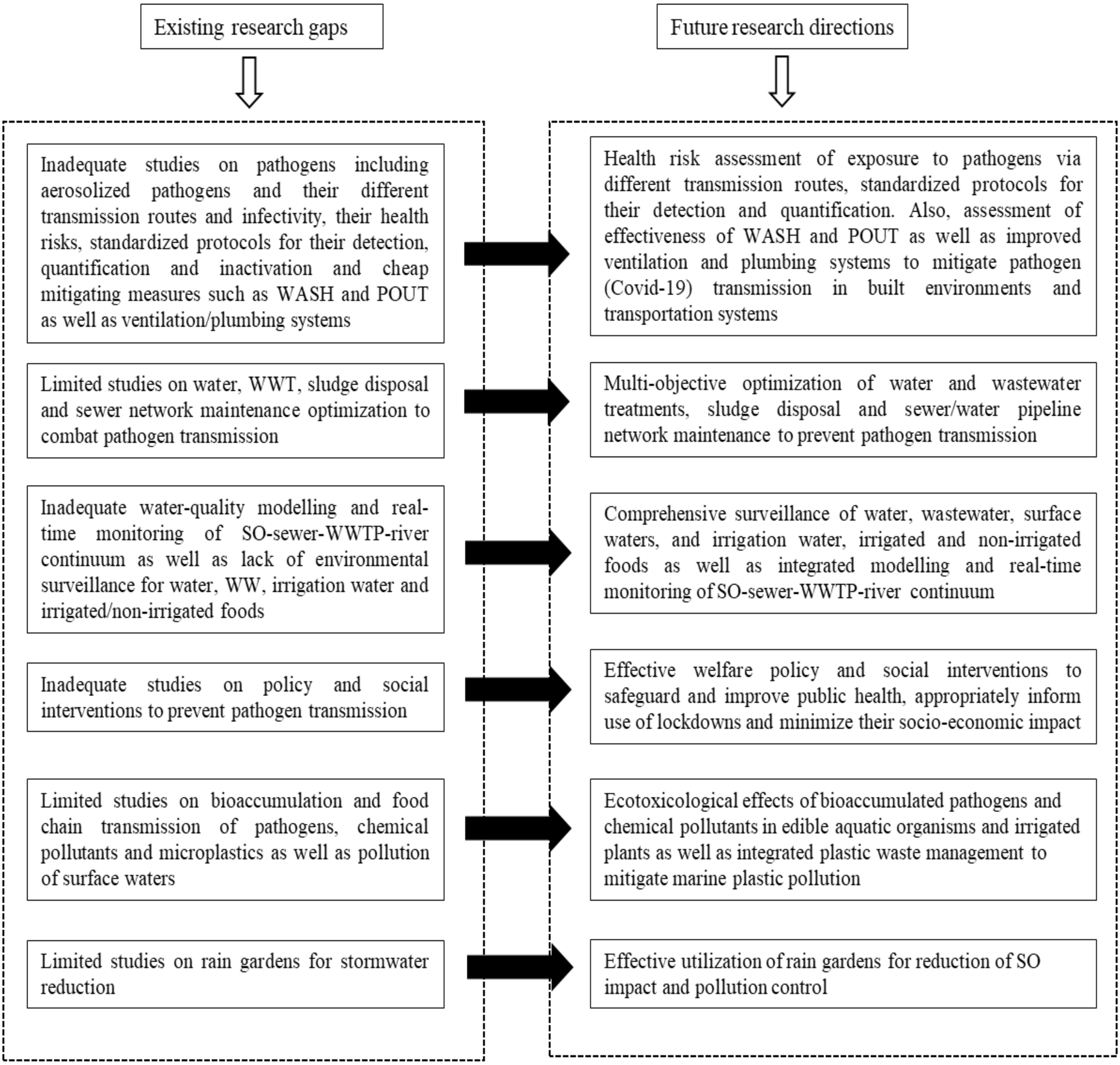


Figure 13. Existing research gaps and future research directions to reduce SO event and safeguard public health

7. Conclusion

SO poses serious threat to global public health and the environment and requires urgent concerted attention. The existing underlying threats have been aggravated by the present Covid-19 pandemic and requires a multidisciplinary approach to find urgent solutions to the identified gaps. Despite progress made, several gaps still exist to be plugged to safeguard public health and improve urban resilience towards pandemics and pathogen transmission. The main findings of this study are:

Based on scientometric analyses, the top six most-active countries in terms of SO and public health are the USA, China, Spain, Australia, Japan, and Canada. Surprisingly, they have also been highly collaborative. The top seven keywords are non-human, sewage, wastewater treatment, water quality, human, and Covid-19. The top five journals are *Science of the Total Environment, Marine Pollution Bulletin, Chemical Engineering Journal,* and *Water Science and Technology*. Based on systematic review, five methodologies were identified. The methods include combined field sampling and laboratory experiments-based studies, review-based studies, and modelling-based studies. Others are hybrid method-based studies and studies based on laboratory/field experiments.

SO impacts surface waters, irrigation water and food crops, drinking water quality, and air quality in built environments. Therefore, comprehensive surveillance of water, wastewater, surface waters, irrigation water, irrigated and non-irrigated foods is required to improve resilience to pathogens. Also, integrated modelling and real-time monitoring of SO-sewer-WWTP-river continuum is crucial in communities exposed to sewer overflow. Multi-objective optimization of water and wastewater treatments, sludge disposal and sewer/water pipeline network maintenance to prevent pathogen transmission is critical to minimize pathogen transmission. In addition, improved ventilation and plumbing systems are required in buildings and transportation systems to curb local pathogen transmission in residential buildings, hospitals, commercial buildings and transportation systems. Increased public awareness on cheap measures such as WASH (water, safety and hygiene) and POUT (point-of-use-water-treatment) such as boiling will also go a long way to safeguard public health. Health risk assessment of exposure to pathogens via different transmission routes is required to appropriately inform the use of lockdowns, minimize their socio-economic impact and guide evidence-based welfare/social policy intervention.

Furthermore, ecotoxicolocal studies on food-chain transmission of pathogens, chemical pollutants and microplastics is important to reveal the effects of these contaminants on aquatic organims and humans and their possible interactions. Also, integrated plastic waste management solutions are needed to curtail global marine pollution and associated consequences. Pre-screening of SO is recommended to minimize transport of plastic litters to marine waters while appropriate disposal systems should be provided in coastal/urban areas experiencing sewer overflow. In addition, soft infrastructure such as raingardens should be exploited and optimized to reduce stormwater burden on existing WWTP during SO. Also, literature revealed elevated health risk exposures to different pathogens for WWTP workers and surrounding communities due to bioaerosols, during swimming in polluted recreational beaches, during urban flooding, toilet flushing and faulty drainage in residential apartments as well as consumption of fishes harvested from polluted waters and polluted drinking water.

Existing research gaps alongside future research directions are highlighted. The major limitation of the existing body of knowledge is lack of integration of modelling and real-time monitoring of sewer oveflow-sewer-WWTP-river continuum. Another limitation is inadequate knowledge on pathogen transmission routes in the built environment.

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Abbreviations

ANN	*Artificial neural network*
Covid-19	*Coronavirus disease of 2019*
DWTP	*Drinking water treatment plant*
E.coli	*Escherichia coli*
EDC	*Endocrine disrupting compounds*
GIS	*Geographic information system*
HAdV	*Human adenovirus*
HPV	*Human papillomavirus*
HPyV	*Human polyomavirus*
ICP-MS	*Inductively coupled plasma mass spectrometry*
ICP-OES	*Inductively coupled optical emission spectrometry*
LC-MS	*Liquid chromatography mass spectrometry*
MERS-COV	*Eastern respiratory syndrome coronavirus*
MPN	*Most probable number*
NoV	*Norovirus*
NoVG1	*Norovirus genogroup 1*
PAH	*Polycyclic aromatic hydrocarbons*
PCA	*Principal component analysis*
POUT	*Point-of-use-treatment*
PPCP	*Pharmaceuticals & personal care products*
PPE	*Personal protective equipment*
RNA	*Ribonucleic acid*
RT-PCR	*Real time-reverse transcription polymerase chain reaction*
RT-qPCR	*Quantitative reverse transcription polymerase chain reaction*
SARS	*Severe acute respiratory syndrome*
SO	*Sewer overflow*
WASH	*Water, sanitation & hygiene*
WBE	*Wastewater-based epidemiology*
WQI	*Water quality index*
WWT	*Wastewater treatment*
WWTP	*Wastewater treatment plant*