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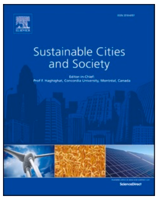

On the Critical Role of Human Feces and Public Toilets in the Transmission of COVID-19: Evidence from China

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ABSTRACT

The surprising spread speed of the COVID-19 pandemic creates an urgent need for investigating the transmission chain or transmission pattern of COVID-19 beyond the traditional respiratory channels. This study therefore examines whether human feces and public toilets play a critical role in the transmission of COVID-19. First, it develops a theoretical model that simulates the transmission chain of COVID-19 through public restrooms. Second, it uses stabilized epidemic data from China to empirically examine this theory, conducting an empirical estimation using a two-stage least squares (2SLS) model with appropriate instrumental variables (IVs). This study confirms that the wastewater directly promotes the transmission of COVID-19 within a city. However, the role of garbage in this transmission chain is more indirect in the sense that garbage has a complex relationship with public toilets, and it promotes the transmission of COVID-19 within a city through interaction with public toilets and, hence, human feces. These findings have very strong policy implications in the sense that if we can somehow use the ratio of public toilets as a policy instrument, then we can find a way to minimize the total number of infections in a region. As shown in this study, pushing the ratio of public toilets (against open defecation) to the local population in a city to its optimal level would help to reduce the total infection in a region.

1. Introduction

The outbreak of COVID-19 diseases spreads very quickly all over the world, infecting millions of people in a very short period. The number of confirmed cases of COVID-19 continues to rise; according to real-time statistics released by the World Health Organization (WHO), the cumulative number of cases as of September 8, 2021, was around 223 million globally.[1] The virus that causes the infection and hence the diseases is formally called Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). The spread of COVID-19 disease is a multi-scenario and multi-factor concept. Although such concept is very different from the virus of SARS-CoV-2, the two terms are used mixedly to express the similar meaning in many situations. However, this study mainly describes the spread of SARS-CoV-2 in a specific scenario. Therefore, even though there are several terms of COVID-19 throughout this paper, when we talk about the transmission, we really mean the SARS-CoV-2 virus.

The surprising speed of the virus's spread created an urgent need to investigate the chain and pattern of transmission of COVID-19. As it is considered a respiratory syndrome, the major route of its transmission is commonly considered to be through respiratory channels. Indeed, most current studies imply that the major routes of transmission of the virus are through respiratory droplets and fomites (Chan, Yuan, & Kok, 2020; Hellewell, Abbott, & Gimma, 2020; Lu, Zhao, & Li, 2020; WHO, 2020). Therefore, people are encouraged to wear face masks to prevent the active virus from entering and lodging in the nasal cavity and upper respiratory tract.

However, it has been more than twenty months since the outbreak of COVID-19, and mankind is yet not certain about its exact transmission route. Now, the exacerbation of the global pandemic indicates that other potential methods of transmission might also exist. More recent studies are emerging, not only in the social vulnerability (Kashem, Baker, & González, 2021), but also in the practical challenges (Poon & Tee, 2021). However, knowledge about other potential vehicles for the spread of SARS-CoV-2 remains to be determined.[2]

As the COVID-19 pandemic evolves to a global disaster, even to be out of control in many countries and regions, we need to seek for new answers by exploring new routes of transmission of the virus of SARS-CoV-2. Up till now, we cannot rule out other routes besides the traditional respiratory route (Dhama, Khan, & Tiwari, 2020), especially the

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fecal-associated routes (Sun & Han, 2021 and many others).

The transmission chain of COVID-19 is still a puzzle. The SARS-CoV-2 virus can survive for a long time, remaining viable on the surface of objects. In fact, China Center for Disease Control and Prevention (CDC, China) released a report on October 17, 2020, saying that it detected a COVID-positive live virus in the samples of imported frozen cod in Qingdao.[3] Under certain environmental conditions, the virus on the surface of an object might lead to infection. In addition, it has been reported that transmission could have occurred from a COVID-positive family whose children smeared feces around their room in a quarantine hotel in Australia. It is possible that the nursing staff was infected by the high viral concentration in feces when they entered the room.[4]

Because "the living environment matters" (Das, Ghosh, & Das, 2021), concern about the possible involvement of human feces as well as wastewater and garbage in the transmission of COVID-19 has been raised since the outbreak of the pandemic (Liu, 2020; Quilliam, Weidmann, & Moresco, 2020). In fact, evidences showing the potential for SARS-CoV-2 to be spread by fecal-oral, fecal-fomite, or fecal-aerosol routes have been accumulated (de Graaf et al., 2017; Arslan, Xu, & El-Din, 2020; de Graaf & Beck, 2017 Ling, Xu, & Lin, 2020; Tian, Rong, & Nian, 2020; Xu, Li, & Zhu, 2020a), which raise concern about public toilets.

Indeed, several incidents led to a suspicion of potential fecal transmission. In June 2020, a couple in Beijing was infected with COVID-19 after a visit to a public restroom, where samples of the environment were confirmed to be positive for COVID-19.[5] In August 2020, an evidence indicates that a woman was infected with coronavirus in the restroom while on a flight from Italy to South Korea.[6] In December 2020, Chengdu experienced a small wave of COVID-19, and according to an official bulletin, people who had gone to a particular public restroom were notified that they should take the nucleic acid test for possible exposure to the virus. Thereafter, the official guide advised people to use the public toilets less or not at all.[7] During the same period, in Wenjiang district in Chengdu, the 29 public toilets there were sanitized 118 times every day.[8] The most typical case was the one in Guangzhou in June 2021, which was confirmed in an official investigation. A person could be infected after only 14 s in a public restroom.[9]

In recent decades, "sustainability" has become a popular topic of discussion. Because people need to use the toilet every day, it can be considered as a fundamental object involved in sustainability in daily life that involves meeting basic needs. However, if everyday activities are associated with the transmission of an infectious disease such as COVID-19, attention needs to be paid to avoid seriously negative outcomes.

After the outbreak of COVID-19, researchers inspected the sewers of university residence halls and found SARS-CoV-2 RNA in wastewater samples.[10] Moreover, a study conducted by the Istituto Superiore di Sanità suggests that SARS-CoV-2 existed in wastewater collected from the entrance of treatment plants in northern Italy.[11] SARS-CoV-2 was also identified in sewage in Brazil[12] and Spain[13] respectively.

Xiao and Torok (2020) suggest that governments should take measures to control the potential threat of reinfection from sewage. In February 1, 2020, China's Ministry of Ecology and the Environment (MEE, China) released a notice about the handling of medical sewage and urban sewage, to standardize the emergency treatment and disinfection requirements of medical wastewater, and to prevent the spread of SARS-CoV-2 through feces and sewage.[14] In August 2020, the US Centers for Disease Control and Prevention (CDC, U.S.A) announced the establishment of a national wastewater surveillance system (NWSS) to help local public health officials to better understand the spread of the COVID-19 in their communities.[15] In addition, the US CDC recommended that workers at wastewater treatment plants take standard precautions to prevent exposure to aerosolized sewage.

In this paper, we conjecture that one possible route of transmission is via public toilets, and our results show strong associations between wastewater and infection. One plausible reason for this result is that people infected with COVID-19 emitted airborne aerosols that were propelled upward and outward when they flushed the toilet. Because the toilets are in a public space, those who enter that area after them could become infected. However, the use of physical barriers (Ren, Xi, & Wang, 2021) and better ventilation (Kong, Guo, & Lin, 2021) may decrease the spread of infection.

As stated above, the transmission chain of COVID-19 still remains unclear. Because the virus can be found in public toilets, wastewater, and sewage, we now suspect the virus can be transmitted in ways other than the traditional respiratory channels. In addition, the concentration of the virus (i.e., virus load) matters a great deal in the transmission of COVID-19. So, this study examines whether human feces and public toilets play a critical role in that transmission. First, we develop a theoretical model that simulates the transmission chain of COVID-19 through public restrooms. Second, we use stabilized epidemic data in China to empirically examine this theory. Finally, we outline policy implications based on our findings.

2. A critical review of related studies

There has been a burst of related studies emerging in recent months of 2021. Hence, we present perhaps the most up-to-date, comprehensive literature review before we formally develop our analysis. Next, we briefly review current support for the potential for fecal transmission and discuss the possible impacts from a public health perspective. By examining the relevant case reports, we provide a valuable reference for the prevention and control of infection with SARS-CoV-2.

2.1. The gastrointestinal (GI) symptoms among COVID-19 patients

In the first strand of related studies, there are many review articles of COVID-19 and its potential relationship with the digestive system. A respiratory disease though it appears to be (Brooks & Bhatt, 2021), as many studies have confirmed high rate of physiopathology with gastrointestinal (GI) symptoms beyond the traditional respiratory system among COVID-19 patients (Devaux, Lagier, & Raoult, 2021; Wang, Yue, & Cai, 2021a), the gastrointestinal tract is now becoming one of the alternative explanations to understand the virus (Sridhar & Nicholls, 2021). The gastrointestinal symptoms have been discussed in (de Almeida and Chehter, 2020), Cortés (2020), Han, Duan, and Zhang (2020), Lin, Jiang, and Zhang (2020), Lv, Jiang, and Chen (2021), Tian et al. (2020), Villapol (2020), among others. Since a large ratio of COVID-19 patients have demonstrated GI symptoms, up to 79.1% (Wang et al., 2021a), it has been used in the diagnosis of COVID-19 as a new focal point (Cipriano, Ruberti, & Giacalone, 2020). But what is the missing link to inspire further investigation (Brooks & Bhatt, 2021)?

One alternative route of infection might be the digestive system, however, previous studies have ignored or underestimated the number of asymptomatic people with early mild GI symptoms (Gu, Han, & Wang, 2020). Studies have shown that COVID-19 depends on the ACE2 host cell factor (Hoffmann, Weber, & Schroeder, 2020; Lu et al., 2020; Zhou, Yang, & Wang, 2020) and can be transmitted through feces by entering host cells through the ACE2 cellular receptor (Zhang, Kang, & Gong, 2020), so the digestive system is a potential route for SARS-CoV-2 transmission. Recent reports also point out that some patients who were infected with COVID-19 had GI symptoms, including diarrhea (Cheung, Hung, & Chan, 2020; Liang, Feng, & Rao, 2020; Yeo, Kaushal, & Yeo, 2020). In addition, some researchers find that some patients infected with COVID-19 have active and prolonged viral infection in their gut, even in the absence of GI symptoms.[16]

2.2. The prevalence and prolonged presence of SARS-CoV-2 RNA in COVID-19 patients

In fact, the prevalence and prolonged discharge in human feces has already been detected and identified of SARS-CoV-2 RNA in COVID-19 patients (Cheung et al., 2020; Gupta, Parker, & Dolwani, 2020; He, Wang, & Li, 2020; Xu et al., 2020a; Zhang, Cen, & Hu, 2021). The ratio of positively tested stool specimens with SARS-CoV-2 RNA can be up to 66.67%, among which 64.29% still test positive even if the patients' test results of pharyngeal swabs are already negative (Chen, Liu, & Liao, 2021a). Thus, the fecal viral activity of SARS-CoV-2 has obtained more and more academic concerns (Zuo et al., 2021). Testing in fecal sample is also recommended to increase the detection sensitivity (Cao, Bao, & Pan, 2021a; Foladori, Cutrupi, & Segata, 2020).

Other studies have shown that COVID-19 can be found in the feces of people who feel sick as well as those without any symptoms (Bai, Yao, & Wei, 2020; Kam, Yung, & Cui, 2020; Mesoraca, Margiotti, & Viola, 2020; Tang, Tong, & Wang, 2020; Wu, Guo, & Tang, 2020). Wang, Li, and Jin (2004)) find that SARS-CoV-1 can survive for more than 17 days in feces and urine. Holshue, Debolt, and Lindquist (2020) report the epidemiological and clinical characteristics of the first confirmed case of COVID-19 infection in the United States. After the patient's hospitalization, the results showed that the stool and respiratory tract samples were COVID-19 positive, but the serum was still negative. Obviously, the virus remains in the feces longer than in the respiratory tract. Studying a stool screening test, Zuo et al. (2021) note that some COVID-19 patients had positive stool tests but negative tests with respiratory samples.

Moreover, Wu et al. (2020) find that viral RNA shed in fecal samples for approximately five weeks after the patients' respiratory samples tested negative for SARS-CoV-2 RNA. Xu et al. (2020a) examine SARS-CoV-2 infection in children and find that eight of ten children tested positive on rectal swabs even after nasopharyngeal testing was negative. Studies in children's specimens of feces show positive RNA up to 30 or even 54 days (Xie, Long, & Ren, 2020).

Xiao, Tang, and Zheng (2020) show that SARS-CoV-2 can be found in feces, and even though the virus is not detected in the respiratory tract, stool samples can remain positive. Zhu, Liu, and Xu (2015) state that viral RNA could be detected in fecal samples from 15 patients with a real-time reverse transcription polymerase chain reaction. Moreover, Mesoraca et al. (2020) write that six fecal specimens became positive for SARS-CoV-2 RNA, while 13 respiratory tests returned negative results 15 days after the first positive respiratory specimens test.

2.3. *The potential fecal-oral transmission*

A natural implication of the fecal viral shedding of SARS-CoV-2 leads to the concern of the potential fecal-oral transmission. In fact, A few studies raise the possibility of fecal-oral transmission based on the extended duration of viral shedding in stool samples. Such gastrointestinal illness induced by COVID-19 indicates high likelihood of transmission route of fecal material (Chen et al., 2021a; Olusola-Makinde et al., 2020). Thus, the possibility of fecal-oral route has become a popular hypothesis which is suggested by the facts shown above (Bonato, Dioscoridi, & Mutignani, 2020; Chen et al., 2021a; Troisi, Venutolo, & Tanyà, 2021). Some scholars even consider it to be the cause of community transmission with a major environmental concern (Jones, Baluja, & Graham, 2020; Mohan, Hemalatha, & Kopperi, 2021). Moreover, it has been prompting from clinical research (Pola, Karnam, & Santhekadur, 2021) to a major public health concern (Panchal, Prakash, Bobde, & Pal, 2021a; Usman, Farooq, & Anastopoulos, 2021).

2.4. *Aerosols: the more critical matter?*

However, the fecal-oral transmission is not the only concern we have. In fact, it may not even be the primary route (Albert, Ruiz, & Peman, 2021). Perhaps, we may need to worry more about the fecal associated aerosols (Cao, Shao, & Jones, 2021b). Now, the respiratory aerosols with much smaller size than the droplets are considered to contribute a lot to the infection of SARS-CoV-2 (Wang, Prather, & Sznitman, 2021b).

In fact, studies on other diseases in the past suggest that the aerosol route can play a contributing role in transmission (Ignatius, Tam, Lee, & Leung, 2004; Salgado, Farr, & Hall, 2002; Atkinson & Wein, 2008; Brankston, Gitterman, & Hirji, 2007; Wong, Lee, & Li, 2010).

2.5. *Concerns of indoor environment*

This would lead to the discussion of built environment (Li, Ma, & Zhang, 2021a; Liu, Liu, & Guan, 2021) and especially indoor environment (Barbieri, Zupin, & Licen, 2021; Ren et al., 2021). In fact, besides the environmental surface (Dargahi, Jeddi, & Vosoughi, 2021), the small and close environment provides scenarios of high risk of aerosols exposure (Ahmadzadeh & Shams, 2021).

Although proper physical isolation measures, such as social distancing and wearing masks (Choi & Shim, 2021; Liao, Liu, & Wang, 2021; Su et al., 2021; Sun, & Zhai, 2020), are effective for reducing the transmission of infection, indoor environments can still be risky, which leaves open the possibility of transmission via feces until this is disproven.

Some scholars have paid attention to the ventilation system which may contribute either positively or negatively to the virus spread (Kong et al., 2021; Senatore, Zarra, & Buonerba, 2021; Sha, Zhang, & Qi, 2021). There is no doubt that optimized ventilation system can decrease the transmission of virus (Dumont-Leblond, Veillette, & Mubareka, 2020). Apart from the ventilation, heating and air conditioning systems also add new concern in their roles with the transmission of SARS-CoV-2 RNA (Horve, Dietz, & Fretz, 2021).

2.6. *The public toilets: why do they matter?*

A typical example of the closed indoor environment with poor hygiene condition is the public restrooms. The risk of exposure in public toilets theoretically comes from aerosol transmission, which has been suggested to be an additional pathway.[17] Flushing produces aerosol sprays, and if the viruses are present in feces, the concern is that inhalation of aerosols is produced by people infected with SARS-CoV-2 when they cough or even speak, which can cause the virus to spread. Even the toilet paper is concerned for its hoarding (Labad, Gonzales-Rodriguez, & Cobo, 2021).

In fact, the aerosol generation with unhealthy outcomes has been studied even before the COVID-19 pandemic (Aithinne, Cooper, & Lynch, 2019). As early as discussed by the classical research of microbiological hazards (Gerba, Wallis, & Melnick, 1975), the aerosol can be generated by toilet plume or flushing which may cause aerosolization (Barker & Jones, 2005; Best, Sandoe, & Wilcox, 2012; Hamilton, Hamilton, & Johnson, 2018; Johnson, Lynch, & Marshall, 2013a, 2013b) or bioaerosol concentrations (Knowlton, Boles, & Perencevich, 2018). In the process, the emission strength can be strong (Lai, Tan, & Li, 2018), which may promote the transmission of virus if there is any according to the fluid dynamics (Li, Wang, & Chen, 2020). An earlier study of hospital toilets also found that the bioaerosol concentrations were significantly greater after fecal waste was flushed down the toilet and might remain in the air for more than 30 min Knowlton et al., (2018).

After the outbreak of COVID-19 pandemic, the risk of fecal transmission in public toilets via bioaerosols has soon obtained attention by researchers both in hospital conditions (Ding et al., 2020) and other scenarios (Schreck, Lashaki, & Hashemi, 2021; Usman et al., 2021). This adds alternative explanations to the "traditional" respiratory droplets. A recent study measuring viral RNA in aerosols at two hospitals in China during the outbreak of COVID-19 found that aerosols were higher in the area near the toilets in a patient's room. This suggests that SARS-CoV-2 might be transmitted through aerosols (Casanova, Rutala, & Weber, 2009; Liu, Ning, & Chen, 2020). Van Doremalen, Bushmaker, and Morris (2020) report that SARS-CoV-2 could stay in the aerosols up to three hours. Li et al. (2020) also find that flushing the toilet can disperse virus-laden aerosols about 3 feet high, which computer simulations show can be inhaled. They indicate that after the toilet is flushed, 40–60% of the particles rose above the toilet seat and hovered in the air.

As Sun and Han (2021) point out, massive number of people in many low-income and developing countries and regions have no access to private sanitary facilities with clean environment, which may become a leak of containment in the virus spread. Even in the developed world, the public restrooms are difficult to maintain high sanitation standards. Besides the fecal related issues, the risk of indoor aerosols oriented viral transmission itself in the enclosed spaces for public use can be high (Chen, Jia, & Han, 2021b; Sun, Li, & Han, 2021).

2.7. Focusing on the wastewater-based epidemiology (WBE)

Moreover, concerns have been raised about whether solid human waste washed into the sewers can cause reinfection. Researchers around the world have traced the spread of SARS-CoV-2 through wastewater and sewage. Some hold an optimistic attitude, believing that this reinfection is unlikely happened because the chemicals added to the water destined for urban sewer pipes are disinfectants which prevent the spread of the virus. Gundy, Gerba, and Pepper (2009) demonstrate that the coronavirus dies off very quickly in wastewater, and the time required for the virus titer to decrease 99.9% (T99.9) is between two and four days.

However, Casanova et al. (2009) state that the coronavirus can remain infectious for long periods in water and pasteurized settled sewage. Previous studies have said that SARS-CoV-1 was detected in sewage from hospitals in China during the SARS outbreak (Lee, 2003; Wang, Li, & Guo, 2005). Bibby and Peccia (2013) detected that different types of human viruses can be discharged into the sewage collection system and concentrated in sewage sludge.

Besides the pioneer research of Liu (2020), now with the complex interaction of human feces and public restrooms, this would eventually make SARS-CoV-2 reach the sewage systems (Ihsanullah, Bilal, & Naushad, 2020; Albert et al., 2021; Giacobbo, Rodrigues, & Ferreira, 2021; Graham, Loeb, & Wolfe, 2021; Javier, Klapsa, & Wilton, 2020; Panchal, Prakash, Bobde, & Pal, 2021a). Naddeo and Liu (2020) consider the spread of COVID-19 throughout wastewater systems. Wang, Hu, and Hu (2020a) claim that the nucleic acid of SARS-CoV-2 was detected in the sewage of two hospitals in China.

In fact, there are many studies show the prolonged survival of SARS-CoV-2 in the environment of wastewater and sewage, which can be up to several days or even longer (Giacobbo et al., 2021). Therefore, wastewater as well as the corresponding treatments become very vulnerable to the transmission of virus (Foladori et al., 2020). As a result, the pipeline and the plumbing systems are turning into hazardous zones (Collivignarelli, Collivignarelli, & Miino, 2020; Dight & Gormley, 2021).

Even before the current pandemic, the aerosolization of wastewater systems was studied for its potential role in the viruses' transmission (Lee, Pruden, & Marr, 2016). Beyond the fecal-oral route, the aerosolized water that is contaminated by SARS-CoV-2 can be the much more dangerous transmission route (de Oliveira, Torres-Franco, & Lopes, 2021). Although some scholars claim "lack of evidence" against the infectious SARS-CoV-2 in feces and sewage in recent study (Albert et al., 2021), such claim itself might be lack of evidence.

Now, the contamination of the aquatic systems by the SARS-CoV-2 virus and especially the potential health consequences of aerosolized wastewater (Usman et al., 2021) have already become a major public health concern (Panchal, Tripathy, & Prakash, 2021b). Up till now, the viral RNA of SARS-CoV-2 has been detected in sewage with wastewater in many countries and regions around the globe, and even in surface waters in some places. Some notable examples are listed alphabetically here, but are not limited to: Canada (D'Aoust, Mercier, & Montpetit, 2021), Finland (Hokajrvi, Rytknen, & Tiwari, 2021), Germany (Agrawal, Orschler, & Lackner, 2021; Westhaus, Weber, & Schiwy, 2021), Hong Kong (Cheung et al., 2020; Xu, Zheng, & Li, 2020b), Hungary (Roka, Khayer, & Kis, 2021), India (Chakraborty, Pasupuleti, & Shankar, 2021; Kumar, Joshi, & Patel, 2021), Iran (Tanhaei, Mohebbi, & Hosseini, 2021), Israel (Bar-Or, Weil, & Indenbaum, 2021), Italy (La Rosa, Mancini, & Ferraro, 2021), Mexico (Coronado, Navarro, & Mosqueda, 2021), Netherlands (Medema, Heijnen, & Elsinga, 2020), Pakistan (Haque, Bukhari, Ejaz, & Zaman, 2021), Qatar (Saththasivam, El-Malah, & Gomez, 2021), Saudi Arabia (Alahdal, Ameen, & Alyahya, 2021), Serbia (Kolarevic, Micsinai, & Szanto-Egesez, 2021), Spain Randazzo, Truchado, & Cuevas-Ferrando, (2020), Switzerland (Fernandez-Cassi, Scheidegger, & Banziger, 2021), the United Kingdom (Hillary, Farkas, & Maher, 2021; Martin, Klapsa, & Wilton, 2020), the United States (Li, Di, & Saingam, 2021c; Sherchan, Shahin, & Patel, 2021; Wang, Green, & Wilder, 2020b), and Venezuela (Chacin-Bonilla & Chacon, 2021).

Many new methods have been proposed to detect the wastewater with SARS-CoV-2 (Haque et al., 2021; Sapula, Whittall, & Pandopulos, 2021). Many scholars now tend to consider the COVID-19 pandemic to be a Wastewater-based epidemiology (WBE). Notable examples are listed but are not limited to water media (Buonerba, Corpuz, & Ballesteros, 2021), "Sewage Epidemiology" (Mackul'ak, Gal, & Spalkova, 2021), shedding dynamics model (Miura, Kitajima, & Omori, 2021), virus spreading surveillance (Anand, Adelodun, & Pivato, 2021), monitor and control of mass transmission (Panchal et al., 2021a), and even clinical breakthrough (Alygizakis, Markou, & Rousis, 2021). Among these, the risk of community infection due to wastewater has already become an editorial concern by the academia (Fielder & Ferrell, 2021). Unfortunately, the community spread due to wastewater happens not only in the developing countries like India which has already led to terrible results (Chakraborty et al., 2021), but also in the developed countries like Canada (D'Aoust et al., 2021).

Then, where would the water in the sewage system finally go to? The freshwater environments and water safety are substantially jeopardized by SARS-CoV-2 RNA (Mahlknecht, Reyes, & Ramos, 2021). In fact, the natural water system such as rivers has already been detected with SARS-CoV-2 (Coronado et al., 2021; de Oliveira et al., 2021; Kolarevic et al., 2021).

2.8. Establishing the early surveillance (warning) system

According to the fecal transmission route, the treatment facilities for municipal wastewater have become the critical node in the fight against COVID-19 (Panchal et al., 2021a; Saththasivam et al., 2021; Sherchan et al., 2021; Wolfem, Archana, & Catoe, 2021). It has been noted that even the treated water samples are tested positive (Randazzo et al., 2020). Therefore, the sanitation process in the wastewater treatment plants (WWTPs) must be reinforced, and it also provides important measure to monitor the epidemiological trend, which is essentially an early surveillance (warning) system (Foladori et al., 2020; Mao, Zhang, & Yang, 2020; Panchal et al., 2021b; Shao, Ge, & Jones, 2021).

If we can monitor the viral load (e.g., how many copies/mL or copies/100 mL) in the water, then we can find a way to estimate the virus spread in the community (Foladori et al., 2020). There can be a functional relationship between the two if proper surveillance (warning) system can be established. In this case, the viral shedding in feces can be parameterized for the Wastewater-based epidemiology (WBE) (LaTurner, Zong, & Kalvapalle, 2021; Miura et al., 2021) or a broader concept of environment (Shao et al., 2021). Furthermore, such surveillance (warning) system can be a very cost-effective way to know the spreading and mutations of SARS-CoV-2 in the population-level prevalence (Gibas, Lambirth, & Mittal, 2021; Kantor, Nelson, & Greenwald, 2021; Li, Kulandaivelu, & Zhang, 2021b; Mackul'ak et al., 2021; Saini & Deepak, 2021; Singh, Kumar, & Kapoor, 2021; Wang et al., 2020b; Wong, Tan, & Ying, 2021; Zhu, Oishi, & Maruo, 2021).

A promising surveillance tool as it appears to be, some scholars believe that the rapid monitoring is at least one of the keys to end the current massive transmission (Panchal et al., 2021b; Zhu et al., 2021). Some even consider it to be a breakthrough in the clinical practice with limited testing capacity in laboratories (Alygizakis et al., 2021), which is superior to the traditional clinical methods in population-level testing (Bar-Or et al., 2021). It has been called the "Sewage Tracking" that aims to detect the presence of SARS-CoV-2 RNA in the sewage samples (Martin et al., 2020). While some focus on the hospital wastewater (Acosta, Bautisca, & Hollman, 2021), some others focus on the wastewater of residential building (Wong et al., 2021) as well as university campus (Gibas et al., 2021).

This may be particularly useful in the developing world (Saini & Deepak, 2021). Indeed, there are already some successful examples, such as the sewage detection of SARS-CoV-2 RNA two weeks before the outbreak in Hungary (Roka et al., 2021), one to two weeks ahead of the official announcement in India (Kumar et al., 2021), three days before the first case in England (Martin et al., 2020), the incidence in Switzerland (Fernandez-Cassi et al., 2021), and others.

Now, hundreds of studies have related COVID-19 with water science (Ji, Zhao, & Wei, 2021). Researchers in top academic journals have called for the establishment of the global database for wastewater surveillance as part of the international cooperation (Bivins, North, & Ahmad, 2020) to support the decision-making in the public health sectors (Lundy, Fatta-Kassinos, & Slobodnik, 2021). Of course, there are uncertainties in every step of the above estimation process (Li, Zhang, & Shi, 2021d), which needs future studies to upgrade it.

2.9. What can we do to add to the literature?

To the best of our knowledge, most of these studies are review or descriptive type of articles. First, few city-wide level evidences are found to support the interaction of public toilets in the SARS-CoV-2 transmission. Second, few proper analytical frameworks are set up to conduct the corresponding research. And these are the gaps that this study tries to fill during this hard time.

3. The model

The initial number of infections in a region is I_0. P_{RR} is the probability of visit to a public restroom by someone who is infected. The infection multiplier of the public restroom is Inf_{RR}. Therefore, the number of new infections equals the initial number of infections times the visits to a public restroom, which can be expressed as follows.

$$I_1 = I_0 P_{RR} Inf_{RR} \tag{1}$$

Thus the ratio of reproduction can be calculated as follows.

$$R_1 = \frac{I_1}{I_0} - 1 = \frac{I_0 P_{RR} Inf_{RR}}{I_0} - 1 = P_{RR} Inf_{RR} - 1 \tag{2}$$

Thus,

$$1 + R_1 = P_{RR} Inf_{RR} \tag{3}$$

If this ratio is the same in every round, then:

$$T_I = I_0 (P_{RR} Inf_{RR})^N \tag{4}$$

where T_I is the total number of infections in a region, and N is the number of rounds in the transmission of the virus. After we take the logarithm on both sides of equation, we obtain:

$$\ln(T_I) = \ln(I_0) + N\ln(P_{RR}) + N\ln(Inf_{RR}) \tag{5}$$

This mathematical model is not the focus of this study. The purpose of introducing the mathematical model (i.e., theory) is to provide a general mechanism of viral transmission with a particular focus that is discussed in depth in the statistical models later. Many purely empirical studies do not have a logically sound mechanism, but ours does have one.

Therefore, beyond the mathematical model (theory), the central interest of this study is the design of a novel statistical method to examine the complex role of public restrooms as well as wastewater and garbage on the transmission of COVID-19 to their interaction.

Eq. (5) has similar empirical implications. With appropriate data, the left-hand side of Eq. (5) becomes the dependent variable, and the right-hand side becomes the independent variables (along with a stochastic error term). However, the complex nature of COVID-19 transmission requires more sophisticated handling with special care.

Although I_0 can be considered as a constant in the regression, P_{RR} is difficult to quantify in reality. We therefore use the ratio of the number of public toilets to the local population in a city or simply use the number of public toilets to represent the likelihood of a visit to a public toilet by someone who is infected; although we do not use them at the same time, we compare the results of different model specifications. In addition, to proxy for Inf_{RR}, we use the local urban population. These two proxies are not perfect because acquiring accurate data on the two key variables might be technically impossible, but they are necessary. Of course, more control variables must be introduced to delve into the transmission of COVID-19 further.

The statistical methods we use in this study are simple but meaningful. In addition to the standard ordinary least squares (OLS) method, we use two-stage least squares (2SLS) with appropriate instrumental variables (IVs) to conduct the empirical estimation. However, the choice of IV is a real challenge for researchers. In this study, the key explanatory variable—the number of public toilets or its ratio to population—can be correlated with the stochastic error term in the regression, which is identified as an endogeneity issue. To correct the inconsistent estimation results, we need to use an appropriate IV, hence, we employ the 2SLS estimation method. In this case, urban residential wastewater or residential garbage is used as the IV, which might show important clues as to the possible intermediate role played by human feces on the transmission of COVID-19.

In fact, their complex relationship might be difficult or even impossible to observe. We can observe the viral concentration in human feces in the laboratory, but doing so in an urban context for a large-scale outbreak, i.e., at a city-wide scale, seems to be difficult or even impossible. When we consider wastewater as well as garbage at the city level, the task becomes even harder.

Our design here is novel (and somewhat "tricky"). The novelty of our design is that we use statistical tests to check whether wastewater or garbage at the city level is explicitly influential in viral transmission or implicit but functional as an intermediary for feces in transmission. Because the exact influence of these important factors at the city level (rather than in the lab) cannot be quantified and measured, if our statistical design passes appropriate statistical tests, then in a statistical sense, we can confirm the impact and interaction of these factors (i.e., human feces, wastewater, and garbage) at the city level.

The specific regression method employed is that of two-stage least squares (2SLS) with appropriate instrumental variables (IVs). The 2SLS model is not new. But the use of a 2SLS model in examining the role and interaction of public restrooms as well as wastewater and garbage is novel, constituting this study's contribution to the literature. The key here is the application of IV in the 2SLS model, so we conduct tests for endogeneity and weak instruments to confirm that our choice of IV is appropriate statistically.

In the endogeneity test with robust F-statistics, the precise value of F does not matter, but we check its corresponding p value for statistical significance (i.e., $p<0.01$, $p<0.05$, $p<0.1$). In performing the Montiel-Pflueger test of weak instruments with effective F-statistics, we check whether the value of F is close to 10, or the higher the better.

To our knowledge, the design of this analytical framework is novel, as discussed further below.

4. Data

This study uses data combined with several sources from China. We select data from China for two reasons. First, the Chinese government began to implement quarantine measures around the country in late

January 2020, and these measures have largely controlled the epidemic situation in China for a long time. Therefore, the data in China, especially at the early stage of transmission, is valuable for the purpose of this study. Second, public health conditions are much better in China than some other countries, such as India. For example, refugees and people in countries or regions at a low socioeconomic stratum often lack clean water and adequate sanitation, which could exacerbate fecal-oral transmission. Consequently, if we find significant results using Chinese data, we can infer that these factors are more critical in other countries, such as India, which could help to explain why the pandemic is spreading so rapidly there.

We obtained the data on confirmed cases of COVID-19 for this study from China's National Health Commission (NHC, China),[18] covering 284 major cities with reported infections with COVID-19. However, the number of infections is constantly changing, so choosing the appropriate study period is challenging. In China, the epidemic of COVID-19 can be divided into roughly two stages. In the first stage, from late January to late March 2020, the infection in mainland China spread from Wuhan, the epicenter, to other provinces, first to those nearby and then to those farther away. Then, in the second stage, new confirmed cases were primarily imported from outside the country. Therefore, for the purpose of studying the possible chain of transmission associated with human feces, the data from the first stage are more valuable. For most of the cities in our dataset, we use numbers of infections confirmed as of the night of March 31, 2020. However, because of the lag in confirmation and reports for the epicenter, for Wuhan as well as surrounding cities in Hubei Province, we use the confirmed numbers at the end of June 2020. As shown in Fig. 1, there appears to be strong correlation between confirmed COVID-19 cases and the number of public toilets in most of the sample cities.

As mentioned earlier, we need to introduce several control variables into our regression. First, we include the distance from a city to the epicenter in mainland China, i.e., Wuhan, as measured with the digital map on Baidu.com.[19] S, we add data on the local urban characteristics for the sample cities, primarily obtained from the *China City Statistical Yearbook 2018*.[20] We pay particular attention to urban wastewater and residential garbage, which might be directly or indirectly linked with human feces. In addition, we include some other variables, such as urban district area, green coverage area, and urban built district, though they are not the primary focus of this paper. All the summary statistics are shown in Table 1.

5. Results

Here, we try to keep the description of the empirical results as clear as possible, since all the results are in Tables 2, 3, and 4. Therefore, in the results section, we try to highlight the comparisons of the results in different models.

5.1. Empirical estimation results using ln(Wastewater) as an instrumental variable

In Tables 2 and 3, we show several groups of empirical estimation results using ln(Wastewater) as the IV. In Table 3, the explanatory variable is "ln(Garbage)," unlike in Table 2. In addition, we differentiate between "ln(Number_of_Latrines)" and "ln(Number_of Latrines_Ratio)" as the explanatory variable. The corresponding OLS version of the models are presented here as well.

In Table 2, which does not consider the impact of garbage, the key focus of this study, i.e., the number of public toilets, tends to be positive and significant in its estimation parameter regardless of its absolute value (e.g., Models (1)-(2) and Models (5)-(6)) or its relative or ratio form (e.g., Models (3)-(4) and Models (7)-(8)), which gives us confidence that the results are in consistent with our expectations. For example, in Model (2), we use logarithmic form of all the variables, so the explanation of the coefficients is in percentage. When the number of public toilets increases by 1%, the confirmed cases of COVID-19 infection increase by 0.807%. In Model (4), the ratio of the number of public toilets has a marginal impact on the increase in COVID-19 cases of 1% to 4.038%. However, Model (4) fails the test of weak instruments as the F-statistic is only 2.694. However, when the variable for garbage is added to the model (Table 3), the number of public toilets is no longer statistically significant in general, which is not the desired outcome. In addition, all the F-statistics in the tests of weak instruments in the 2SLS models in Table 3 are less than 10, which means they fail the tests.

Notably, ln(Dist_to_Wuhan) is generally negative and significant in all models, and its estimation parameters appear to be robust among different model specifications. For example, in Model (2), the result shows that an increase of 1.372% in the number of infections occurs in locations that are 1% closer to Wuhan (i.e., a smaller distance). In Model (4), this marginal impact is 1.265%, which is very similar to that in Model (3). This result shows that the distance from Wuhan is a very powerful control variable that can help us to isolate the local characteristic of the cities from the COVID-19 transmission. Additionally, ln (Urban_District_Population) is typically found to be positive and significant in the OLS estimations. Only in Model (4) in Table 2 showing its coefficient is positive and significant under 2SLS estimation. As shown in the results, the marginal impact is 1% to 1.428%.

Moreover, the inclusion of ln(Urban_District_Area) or ln(Green_Coverage_Area) has no persuasive results. In Model (6), the result shows that a 1% increase in the green coverage area would decrease infections by 0.615%. In Table 3, although the coefficients of ln(Garbage) are

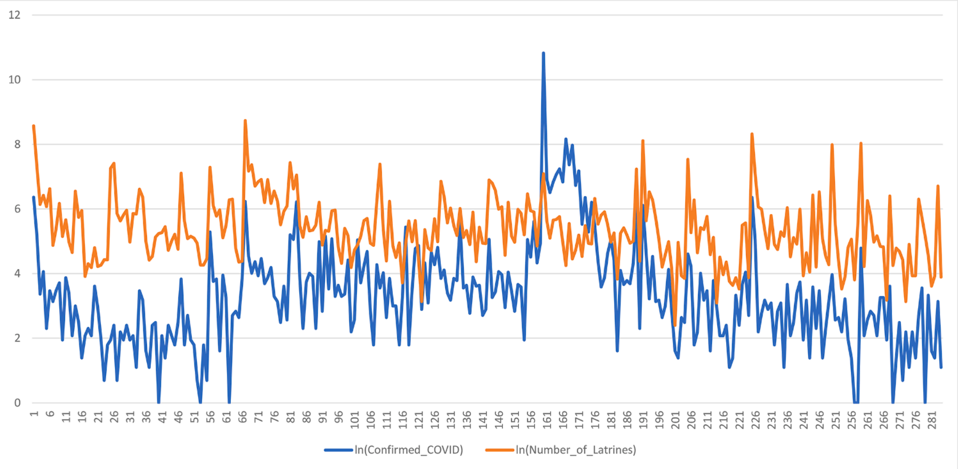

Fig. 1. The correlation of confirmed COVID-19 cases and the number of public toilets (latrines).

Table 1
The summary statistics ($N = 284$).

Variables	Explanation	Unit	Mean	Std. Dev.	Min	Max
Confirmed_COVID	Number of confirmed COVID cases as reported.	Case	286.169	2999.618	1	50,340
Number_of_Latrines	Number of public latrines.	Unit	391	669.788	11	6221
Dist_to_Wuhan	Distance to Wuhan.	km	928.811	543.180	17.89	2777.8
Urban_District_Population	Urban district population.	10,000	183.5	279.540	15.73	2489.92
Urban_District_Area	Urban district area	km^2	2938.3	3577.89	132.3	43,263.1
Green_Coverage_Area	Green coverage area	km^2	9861	18,519.37	411	154,742
Built_District	Built district area	km^2	6628	9454.572	196	88,844
Wastewater	Annual quantity of wastewater discharged.	10,000 m3	14,811	27,511.76	540	229,526
Garbage	Annual quantity of garbage collected and transported.	10,000 ton	62	106.584	5	925

Note: Please see the Data section in the main text for more explanations of the variables.

Table 2
Empirical estimation results using instrumental variable (IV) of ln(Wastewater) without ln(Garbage) (Dependent variable: ln(Confirmed_COVID), $N = 284$).

	Model (1) OLS	Model (2) 2SLS (IV: ln (Wastewater))	Model (3) OLS	Model (4) 2SLS (IV: ln (Wastewater))	Model (5) OLS	Model (6) 2SLS (IV: ln (Wastewater))	Model (7) OLS	Model (8) 2SLS (IV: ln (Wastewater))
ln(Number_of_Latrines)	0.277***	0.807***			0.276***	1.580***		
	(0.079)	(0.183)			(0.088)	(0.466)		
ln(Number_of Latrines_Ratio)			0.226**	4.038*			0.206**	−67.489
			(0.092)	(2.428)			(0.091)	(655.082)
ln(Dist_to_Wuhan)	−1.309***	−1.372***	−1.276***	−1.265**	−1.307***	−1.379***	−1.295***	−0.252
	(0.107)	(0.111)	(0.111)	(0.213)	(0.104)	(0.117)	(0.108)	(10.823)
ln(Urban_District_Population)	0.630***	0.130	0.922***	1.428***	0.633***	0.050	0.797***	−12.445
	(0.117)	(0.207)	(0.084)	(0.342)	(0.117)	(0.241)	(0.110)	(128.017)
ln(Urban_District_Area)	0.006	0.060	−0.042	−0.378				
	(0.082)	(0.091)	(0.085)	(0.266)				
ln(Green_Coverage_Area)					0.001	−0.615**	0.109	7.319
					(0.098)	(0.281)	(0.090)	(69.335)
Adjusted R^2	0.630	0.571	0.621	NA	0.630	0.336	0.623	NA
Endogeneity Test (Robust regression F-stats)		11.736***		19.849***		17.655***		23.567***
Montiel-Pflueger robust weak instrument test (Effective F-stats)		63.322		2.694		17.478		0.011

Note: The values of the constant terms are not reported. Robust Std. Err. in parentheses. *** $p \leq 0.01$, ** $0.01 < p < 0.05$, *$0.05 < p < 0.1$.

Table 3
Empirical estimation results using instrumental variable (IV) of ln(Wastewater) with ln(Garbage) (Dependent variable: ln(Confirmed_COVID), $N = 284$).

	Model (9) OLS	Model (10) 2SLS (IV: ln (Wastewater))	Model (11) OLS	Model (12) 2SLS (IV: ln (Wastewater))	Model (13) OLS	Model (14) 2SLS (IV: ln (Wastewater))	Model (15) OLS	Model (16) 2SLS (IV: ln (Wastewater))
ln(Number_of_Latrines)	0.126	1.624			0.153*	5.878		
	(0.084)	(1.068)			(0.086)	(8.794)		
ln(Number_of Latrines_Ratio)			0.136	−2.247			0.144*	−2.086
			(0.089)	(1.992)			(0.085)	(1.288)
ln(Dist_to_Wuhan)	−1.353***	−1.361***	−1.346***	−1.448***	−1.336***	−1.407***	−1.334***	−1.334***
	(0.110)	(0.124)	(0.111)	(0.197)	(0.101)	(0.308)	(0.102)	(0.147)
ln(Urban_District_Population)	0.316*	0.161	0.388**	−0.638	0.387***	−0.099	0.448***	−0.283
	(0.166)	(0.245)	(0.166)	(0.917)	(0.141)	(0.867)	(0.137)	(0.500)
ln(Urban_District_Area)	0.055	0.029	0.040	0.350				
	(0.086)	(0.109)	(0.089)	(0.308)				
ln(Green_Coverage_Area)					−0.176	−1.262	−0.147	−0.140
					(0.110)	(1.800)	(0.106)	(0.218)
ln(Garbage)	0.424***	−0.744	0.485***	1.145*	0.521***	−3.069	0.584***	1.093***
	(0.134)	(0.869)	(0.121)	(0.607)	(0.147)	(5.541)	(0.142)	(0.417)
Adjusted R^2	0.6420	0.304	0.642	NA	0.645	NA	0.644	NA
Endogeneity Test (Robust regression F-stats)		3.597*		5.070**		7.666***		9.558***
Montiel-Pflueger robust weak instrument test (Effective F-stats)		3.612		2.106		0.455		4.090

Note: The values of the constant terms are not reported. Robust Std. Err. in parentheses. *** $p \leq 0.01$, ** $0.01 < p < 0.05$, *$0.05 < p < 0.1$.

generally positive and significant, it distorts other aspects of the models, in particular the primary research target of this study, i.e., the number of public toilets.

So, how can our empirical results be improved?

5.2. Empirical estimation results using ln(Garbage) as an instrumental variable

In Table 4, we use ln(Wastewater) as the explanatory variable and ln

Table 4
Empirical estimation results using instrumental variable (IV) of ln(Garbage) (Dependent variable: ln(Confirmed_COVID), $N = 284$).

	Model (17) OLS	Model (18) 2SLS (IV: ln (Garbage))	Model (19) OLS	Model (20) 2SLS (IV: ln (Garbage))	Model (21) OLS	Model (22) 2SLS (IV: ln (Garbage))	Model (23) OLS	Model (24) 2SLS (IV: ln (Garbage))
ln(Number_of_Latrines)	0.183**	0.598*			0.191**	0.819**		
	(0.086)	(0.313)			(0.086)	(0.420)		
ln(Number_of Latrines_Ratio)			0.209**	0.972*			0.205**	1.147*
			(0.087)	(0.545)			(0.088)	(0.620)
ln(Dist_to_Wuhan)	−1.299***	−1.323***	−1.292***	−1.303***	−1.294***	−1.318***	−1.289***	−1.298**
	(0.102)	(0.100)	(0.104)	(0.107)	(0.104)	(0.103)	(0.105)	(0.112)
ln(Urban_District_Population)	0.432***	0.318**	0.522***	0.668***	0.448***	0.324**	0.529***	0.730***
	(0.124)	(0.160)	(0.119)	(0.153)	(0.128)	(0.162)	(0.126)	(0.187)
ln(Green_Coverage_Area)	−0.279**	−0.379***	−0.258**	−0.343**				
	(0.123)	(0.146)	(0.120)	(0.142)				
ln(Built_District)					−0.342*	−0.704**	−0.273	−0.464*
					(0.186)	(0.326)	(0.182)	(0.258)
ln(Wastewater)	0.489***	0.344**	0.555***	0.562***	0.511***	0.416***	0.552***	0.609***
	(0.116)	(0.155)	(0.114)	(0.127)	(0.140)	(0.158)	(0.137)	(0.165)
Adjusted R^2	0.651	0.623	0.6513	0.569	0.648	0.587	0.648	0.522
Endogeneity Test (Robust regression F-stats)		2.364		2.797*		3.047*		3.372*
Montiel-Pflueger robust weak instrument test (Effective F-stats)		24.047		9.855		18.872		9.647

Note: The values of the constant terms are not reported. Robust Std. Err. in parentheses. *** $p \leq 0.01$, ** $0.01 < p < 0.05$, *$0.05 < p < 0.1$.

(Garbage) as the IV. The overall performance of this group of models appears to be better: the number of public toilets is positive and significant in its estimation coefficients, either in its original form or the ratio form. In Model (22), when the number of public toilets increases by 1%, the number of COVID-19 infections rises by 0.819%. Then, in Model (24), the marginal impact is 1% to 1.147% using the ratio version of the number of public toilets.

With regard to the control variables, ln(Dist_to_Wuhan) and ln (Urban_District_Population) are as good as expected in the estimation parameters. In Model (22), the estimated marginal impact of the distance from Wuhan is 1% to −1.318%, and the coefficient in Model (24) is −1.298, which is still very close in percentage terms. In addition, ln (Green_Coverage_Area) and ln(Built_District) tend to have negative and significant estimation coefficients. This result means that larger areas tend to have a lower number of infections. In Model (20), the marginal impact of the green coverage area on local infections is 1% to −0.343%, and in Model (22) the impact of built area on the number of infections is 1% to −0.704%. Although the reasons for these results might be complex, when cities have more such areas, viral transmission is more difficult, hence those cities have fewer confirmed COVID-19 infections.

Notably, we combine the use of the IV ln(Garbage) and the explanatory variable ln(Wastewater) in the group of models shown in Table 4. The coefficients of ln(Wastewater) are positive and statistically very significant in all these models, which confirms the role of wastewater in the urban transmission of COVID-19. The marginal impact of wastewater on infections is estimated as 1% to 0.416% in Model (22), compared with 1% to 0.609% in Model (24). In early August 2021, Zhengzhou experienced widespread flooding, and shortly afterwards it had a small wave of COVID-19 infection. This might be a typical example of the role of wastewater in COVID-19 transmission.

Although the endogeneity test fails in Model (18), it passes in Model (20), (22), and (24). The results of the weak instrument test are generally good, either close to the empirically critical value of 10 or much larger than 10. Among all the models in this group, we prefer Models (22) and (24). Although the statistical results appear to be slightly better in Model (22), in terms of more significant estimation coefficients (larger R^2 value and F-statistics in the test of weak instruments), the two models essentially differ very little.

6. Discussion

Many scholars have placed their concerns on the low-income countries or developing world where there is inadequate water for sanitation use (Castro, Bernegossi, & Sousa, 2021; Eichelberger, Dev, & Howe, 2021; Troisi et al., 2021) or the usage of virus-contaminated water (Adelodun, Ajibade, & Ighalo, 2021). In such scenarios, the fecal-oral transmission of SARS-CoV-2 has much higher risk (Chacin-Bonilla et al., 2021) and the community spread would be a more common consequence due to poor sanitation infrastructure (Eichelberger et al., 2021).

In the more vulnerable case, the squat toilets (especially with lidless designs) become new risk factors (Sun & Han, 2021) and things may get harder in the scenarios of open defecation. In fact, open defecation is the common practice with a high proportion of population in some countries

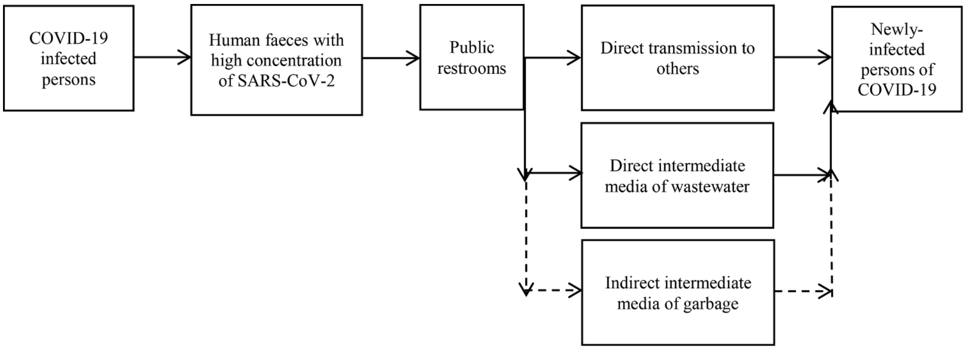

Fig. 2. A simple illustration of the transmission chain of COVID-19.

with large number of COVID-19 cases (Sun & Han, 2021). Some scholars have mentioned India, where the dense population along with the poor sanitation condition make things worse (Panchal et al., 2021b).

In the previous section, we showed that human feces and public toilets might play a critical role in the transmission of COVID-19. In regions with relatively poor public sanitation, where human waste might be openly exposed, viral transmission could be even greater. Therefore, using the infection multipliers Inf_{OPEN} and Inf_{RR}, respectively, we consider the effect of open exposure of human feces in the environment at open and public restrooms. Now we revise Eq. (4) as follows.

$$T_I = I_0(P_{RR}Inf_{RR})^N + I_0((1-P_{RR})Inf_{OPEN})^N \tag{6}$$

Because we are particularly interested in how the ratio of P_{RR} affects the total number of infections T_I, we take the first derivative of T_I with respect to P_{RR}.

$$\frac{\partial T_I}{\partial P_{RR}} = I_0N(P_{RR}Inf_{RR})^{N-1}Inf_{RR} - I_0N((1-P_{RR})Inf_{OPEN})^{N-1}Inf_{OPEN} = 0 \tag{7}$$

Simplifying this equation yields:

$$\frac{P_{RR}}{1-P_{RR}} = \left(\frac{Inf_{OPEN}}{Inf_{RR}}\right)^{\frac{N}{N-1}} \tag{8}$$

By solving for P_{RR} in Eq. (8), we obtain the "optimal" value as follows:

$$P_{RR}{}^{*} = \frac{\left(\frac{Inf_{OPEN}}{Inf_{RR}}\right)^{\frac{N}{N-1}}}{\left(1+\left(\frac{Inf_{OPEN}}{Inf_{RR}}\right)^{\frac{N}{N-1}}\right)} \tag{9}$$

Eq. (9) shows that the value of $P_{RR}{}^{*}$ must be between 0 and 1. Therefore, it satisfies the requirement of probability. However, we do not know whether this "optimal" value is the maximum or the minimum. Thus, we need to examine the second-order condition. Therefore, we differentiate T_I with respect to P_{RR} twice as follows.

$$\begin{aligned}\frac{\partial^2 T_I}{\partial P_{RR}{}^2} &= I_0NInf_{RR}(N-1)(P_{RR}Inf_{RR})^{N-2}Inf_{RR} - I_0NInf_{OPEN}(N-1)((1-P_{RR})Inf_{OPEN})^{N-2}Inf_{OPEN}(-1)\\ &= I_0N(N-1)Inf_{RR}{}^2(P_{RR}Inf_{RR})^{N-2} + I_0N(N-1)Inf_{OPEN}{}^2((1-P_{RR})Inf_{OPEN})^{N-2}\end{aligned} \tag{10}$$

It is not difficult for us to conclude that $\frac{\partial^2 T_I}{\partial P_{RR}{}^2} > 0$. We therefore confirm that the "optimal" value of $P_{RR}{}^{*}$ is the minimum.

These findings have very strong policy implications in the sense that if we can use the ratio of public toilets (against open defecation) to the local population in a city or simply the number of public toilets (i.e., $P_{RR}{}^{*}$) as a policy instrument, then we can minimize the number of total infections in a region due to exposure at public toilets as well as open defecation.

7. Conclusions

This study presents novel insights into potential COVID-19 infection after fecal exposure at public toilets. It briefly reviews the current supports for the possibility of fecal transmission and discusses the possible impacts from a public health perspective. First, a theoretical model is employed. Second, the statistical connection is established between infection and public sanitation. Then, it statistically simulates the transmission chain of COVID-19 at public restrooms and concludes that wastewater, along with garbage, promote the transmission of COVID-19. The results can provide a valuable reference for the prevention and control of the ongoing pandemic.

So, we can draw a conclusion with very strong statistical significance that wastewater directly promotes the transmission of COVID-19 within a city. However, the role of garbage in this transmission chain is more indirect in the sense that garbage has a complex relationship with public toilets, and it promotes the transmission of COVID-19 within a city through the interaction of public toilets and human feces. The complicated potential transmission chain of COVID-19 is illustrated in Fig. 2.

These findings in this study may be of particular importance for India, as it suffers from relatively poor public sanitation conditions, which might contribute to its rapid increase in COVID-19 infection. As shown above, increasing the ratio of public toilets (against open defecation) to the optimal level would help to reduce the total infection in a region. In addition, as shown in the empirical results, effective control of urban wastewater and residential garbage would help to cut the transmission chain of COVID-19. The findings in this study can be of general interest and applied elsewhere. We therefore hope that this study can provide new clues which can contribute to the control of COVID-19 during such a time with hardship.

Because the information and data currently available are rather limited, our discussion lacks many important factors. For example, wearing face masks and washing hands can effectively reduce fecal exposure. Critical information on wearing face masks and washing hands is missing under the circumstances of human feces and public toilets. In addition, some other temporal factors, such as how long the virus remains transmissible, are also important. Furthermore, we should also consider the impact of some auxiliary equipment such as the ventilation system (e.g., exhaust fans), which might already be installed. These factors could also play a significant role in COVID-19 transmission and should be examined in future studies.

Notes

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Declaration of Competing Interest

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

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