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TOPICAL REVIEW

Bottled water quality and associated health outcomes: a systematic review and meta-analysis of 20 years of published data from China

Alasdair Cohen[1,2,*], Jingyi Cui[3], Qingyang Song[3], Qiwen Xia[3,4], Jiexuan Huang[3], Xinjia Yan[3,4], Yalu Guo[5], Yixin Sun[5], John M Colford Jr[6] and Isha Ray[2,4]

[1] Department of Population Health Sciences, Virginia Polytechnic Institute and State University, 205 Duck Pond Dr Blacksburg, VA, 24061, United States of America
[2] Berkeley Water Center, University of California, Berkeley, CA, United States of America
[3] College of Letters and Science, University of California, Berkeley, CA, United States of America
[4] Rausser College of Natural Resources, University of California, Berkeley, CA, United States of America
[5] College of Engineering, University of California, Berkeley, CA, United States of America
[6] School of Public Health, University of California, Berkeley, CA, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: alasdair.cohen@linacre.oxon.org

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Abstract

Bottled water is a rapidly growing yet relatively understudied source of drinking water globally. In addition to concerns about the safety of bottled water, the adverse environmental health and social impacts associated with bottled water production, distribution, consumption, and reliance are considerable. Our objective was to comprehensively review, analyze, and synthesize ∼20 years of publicly available data on bottled water quality and associated health outcomes in China. We conducted a systematic review and meta-analysis of publicly available studies of bottled water quality and associated health outcomes in China published between 1995 and early 2016 (in Chinese and English). We pre-specified and registered our study protocol, independently replicated key analyses, and followed standardized reporting guidelines. Our search identified 7059 potentially eligible records. Following screening, after full-text review of 476 publications, 216 (reporting results from 625 studies) met our eligibility criteria. Among many findings, 93.7% (SD = 10.1) of 24 585 samples tested for total coliforms ($n = 241$ studies), and 92.6% (SD = 12.7) of 7261 samples tested for nitrites ($n = 85$ studies), were in compliance with China's relevant bottled water standards. Of the studies reporting concentration data for lead ($n = 8$), arsenic ($n = 5$), cadmium ($n = 3$), and mercury ($n = 3$), median concentrations were within China's standards for all but one study of cadmium. Only nine publications reported health outcome data, eight of which were outbreak investigations. Overall, we observed evidence of stable or increasing trends in the proportions of samples in compliance over the ∼20 year period; after controlling for other variables via meta-regression, the association was significant for microbiological but not chemical outcomes ($p = 0.017$ and $p = 0.115$, respectively). Bottled water is typically marketed as being safe, yet in most countries it is less well-regulated than utility-supplied drinking water. Given the trend of increasing bottled water use in China and globally—and the associated environmental health impacts—we hope this work will help to inform policies and regulations for improving bottled water safety, while further highlighting the need for substantially expanding the provision of safe and affordable utility-supplied drinking water globally.

1. Background and justification

From the 1990s on, global consumption of bottled water has grown rapidly as it has expanded from markets primarily centered in high-income countries (HICs) to those in low- and middle-income countries (LMICs). The majority of the world's bottled water is now consumed in LMICs [1]. Global growth in bottled water consumption is attributed to consumer demand—driven by perceptions that it is safe and convenient—and is fueled by widespread marketing [2]. Studies on consumer preferences in HICs find that perceived safety and convenience are the primary reasons for bottled water use [3, 4]. While utility-provided safe water access has expanded over the last few decades in most large LMICs, consumption of bottled water has increased far more rapidly [5].

Compared with water utilities that supply piped drinking water (municipal water), regulations for bottled water production in LMICs and HICs are typically less rigorous, and water quality testing and monitoring are required far less frequently. One of the few relatively extensive and publicly available studies on bottled water in the USA concluded that bottled water was not necessarily safer than tap water overall, and ∼20% of the brands tested were contaminated at levels above California's standards [6].

Beyond concerns about the safety of bottled water, the negative social and environmental health impacts associated with bottled water production, distribution, consumption, and reliance are considerable. Bottled water costs hundreds to thousands of times more per liter than treated piped water [2, 6], and the negative environmental impacts associated with single-use plastic bottle production and disposal have become a global concern [7]. Life cycle assessments of bottled water production, transportation, and associated waste help quantify the scope of adverse environmental impacts and demonstrate that contributions to greenhouse gas emissions are orders of magnitude higher than those associated with utility water supply [8, 9]. In recent years, multiple studies have found microplastic contamination to be near-ubiquitous in surface waters, and frequently detected in bottled water samples as well [10, 11].

At this writing, we are aware of only two published bottled water focused systematic reviews. Williams *et al* [12] conducted a relatively comprehensive review focused on fecal contamination in packaged and bottled water in LMICs; however, as the authors noted in their review, they did not include results from China due to the language barrier. The other systematic review focused only on fluoride concentrations in bottled water [13], but likewise did not review Chinese-language results. In addition, in a recently published non-systematic review [14] focused on emerging contaminants (including microplastics), as well as contamination attributed to the types of plastic used for water bottles, the authors did not appear to include results from Chinese-language publications. This is noteworthy when one considers that in 2013, China surpassed the USA to become the world's largest market for bottled water by volume [15]. Furthermore, limited available data indicate that even in rural China more and more households are turning to bottled water (19 l bottles) as their primary source of drinking water [16, 17].

Thus, there appears to be a substantial 'China gap' in the bottled water research literature. China's population is large, its consumption of bottled water is increasing, and it has a relative wealth of publicly available data from published studies on bottled water quality—in contrast to the relatively limited bottled water focused research literature from the USA or Europe. To address this research gap, we conducted a systematic review and meta-analyses focused on bottled water contamination and associated health outcomes in China. The objective of this work was to synthesize publicly available data on bottled water contamination in China published over a period of approximately two decades, analyze data and trends, and attempt to shed light on the underlying causes of reported bottled water contamination.

2. Methods

We conducted a systematic review of published and publicly accessible studies on bottled water contamination and associated health outcomes in China. We registered our study protocol with the International Prospective Register of Systematic Reviews (PROSPERO, 2016:CRD42016048863, www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42016048863) and on Open Science Framework (OSF; including our search terms, sets, code, and relevant Chinese/English translations: https://osf.io/yqbdy). All statistical analyses were conducted using Stata (v.15), and our primary analyses were independently replicated using R (v.4.0.3). This manuscript was prepared in accordance with the PRISMA reporting guidelines [18], and a completed checklist is provided in the last section of the supplementary material (SM).

2.1. Eligibility criteria

We wished to collect and analyze data from any study or investigation of bottled water quality in China. Studies were considered eligible if they measured, quantified, evaluated, assessed, or otherwise tested bottled water samples in China for microbiological and/or chemical contaminants (including heavy metals and radionuclides, but not microplastics), reported original analyses and results, were conducted during or after 1990, and were published between 1995 and early 2016. We did not limit our eligibility based on who evaluated the water quality (universities, government agencies, private companies, other) or based on the type of study design, use of comparison groups, controls, or specific water sampling methods. For the purposes of this review, bottled water was defined as any type of packaged drinking water.

For our key outcome measures, we considered any microbiological contaminants with known links to health to be eligible (whether reported as presence/absence, percentage of samples meeting national/local standards, or mean or median concentrations), provided that such outcomes were directly assessed/measured. Studies based on qualitative descriptions of bottled water quality were not considered eligible. We used these same criteria for chemical contaminants with known or suspected links to health (organic, inorganic, radionucleic, disinfection byproducts). Similarly, we considered any health outcomes with direct or hypothesized links to the consumption of bottled water to be eligible, provided the study also assessed at least one indicator of bottled water contamination. Additional details on our inclusion and exclusion criteria are provided in our PROSPERO protocol (2016:CRD42016048863).

2.2. Search strategy

To identify potentially eligible studies, we searched the primary Chinese-language databases, CNKI (www.cnki.net/) and Wanfang (http://librarian.wanfangdata.com.cn), as well as the online databases PubMed/MEDLINE, EMBASE, and Web of Science. We limited our searches to all records (English or Chinese) published from 1995 to April 2016, when the searches were conducted.

For CNKI, we searched titles and abstracts in six separate databases; for Wanfang we searched titles, keywords and abstracts in nine separate databases. For the Chinese-language databases we used three sets of search terms to identify all records related to: *bottled water, microbiological contaminants*, and/or *chemical contaminants*. For water contaminants (microbiological, chemical, etc) we included all parameters listed across China's official Drinking Water Standards at the time of the search, as well as any additional parameters listed in drinking water standards of the World Health Organization and US Environmental Protection Agency.

For the databases PubMed/MEDLINE, EMBASE, and Web of Science, early piloting of our search terms and sets showed that there were very few records related to bottled water in China. Therefore, to ensure that we identified all potentially eligible records in these three databases, we used search sets and search terms for *bottled water* and *China* (all variants of the country name), and did not use search sets and terms to specify individual microbiological and chemical parameters. To ensure that we did not inadvertently overlook non-Chinese language records using the term 'packaged water' (rather than 'bottled water'), a search for 'packaged water' and the variants of 'China' (e.g. 'PR China') was also conducted via a hand-search using Google Scholar.

All search sets and terms, as well as English translations of Chinese search terms, the search code used for database searches, as well as additional notes, are available online on OSF (at https://osf.io/yqbdy).

2.3. Record screening, data extraction, and derivation protocols

Three reviewers (XY, QX, QS) screened all available titles and abstracts to identify potentially eligible records for full-text review. For the initial record screening step, to avoid inadvertent bias from viewing author name/s, publication type, journal names, etc, only the record titles and abstracts were reviewed. Any records that, based on the content in the title and/or abstract, could have possibly discussed bottled water related analyses in China were retained. To assess inter-rater reliability and evaluate the potential need for full duplicate title/abstract screening, 100 records were selected at random and independently screened by all three reviewers (XY, QX, QS).

Five researchers (QS, QX, JC, PD, JT) reviewed all the potentially eligible full-text records to determine eligibility for data extraction. For each eligible study with extractable data, data was entered into a pre-specified data extraction template (using Google Sheets). To assess the accuracy of the data extraction, data from a random selection of ∼10% of eligible full text records were extracted independently by pairs of reviewers. Following initial data review, to facilitate data cleaning three researchers (QS, QX, JC) reviewed the extracted data for all full-text records assessed to be eligible for inclusion. Given the number of parameters for which we sought to extract data, following these steps we conducted extensive quality control and data cleaning over a period of multiple years.

2.4. Data analyses

Assuming sufficient data was available, our pre-specified objective was to conduct meta-analyses for all primary contaminant classes as well as for specific contaminants, indicators of contamination, and testing methods. For our analyses of health outcomes, we anticipated that inter-study variability (resulting from differences in study designs, bottled water types, sample collection methods, analytic protocols, etc), as well as random error, would be best addressed by using meta-analysis with a random-effects based weighting. If the data structure permitted, we also pre-specified to conduct a meta-regression analysis (with random effects).

We pre-specified subgroup analyses in our protocol (and also as a means of evaluating expected heterogeneity, using standard methods such as the I-squared statistic). To assess studies by climatic region, we binned studies based on province into four categories [19]: cold and mild temperate, warm temperate, mild subtropical, and subtropical/tropical (see table S1 available online at stacks.iop.org/ERL/17/013003/mmedia).

We conducted meta-regression analyses to assess heterogeneity and potential confounders, using a generalized linear model with a logit link, binomial distribution, and cluster-robust standard errors (treating included eligible papers as clusters to adjust for outcomes from multiple sub-studies). For our meta-regression analyses, our outcome variable was the reported passing rate (expressed as a proportion) for all microbiological and chemical parameters for which we extracted data, and we analyzed the following covariates: the year of study publication, the study setting (rural, urban, other), the study setting climate, an indicator of provincial level economic consumption (low, medium, and high levels), the type/source of the bottled water (mineral, spring, purified, other), and the number of bottled water samples analyzed. Because many publications reported multiple results for the same parameters from different sub-studies, standard errors were adjusted to control for the clustered nature of the data.

2.5. Assessment of bias

We anticipated significant heterogeneity in study methods and reporting among those records eligible for data extraction. To assess risk of bias (ROB), we adapted approaches from previously published systematic reviews [20–22] and created a composite index based on six variables (assessing sampling methods and how study methods and protocols were reported), each of which was scored on a three-point scale (see table S2 for details). To assess potential publication bias, we used standard methods (Egger's test, funnel plots).

3. Results

3.1. Search and screening results

Our search resulted in the identification of 7059 potentially eligible records (after duplicate removal) (figure 1). Through title and abstract screening, we identified 476 potentially eligible records. For the randomly selected sub-sample of 100 records the kappa statistic for three reviewers (XY, QX, QS) with two possible outcomes (yes, no) was 0.83 ($z = 14.3$, $p < 0.001$), indicating a very high degree of inter-rater agreement [23]; therefore, we did not conduct additional duplicate review for the title/abstract screening stage. Of the 476 records identified for full-text review, we were unable to find the full text for 39, and a further 221 were excluded for various reasons, as outlined in figure 1 (additional details in table S3).

3.2. Characteristics of eligible studies with extractable data

All 216 of the eligible records with extractable data were journal publications; 110 reported results for microbiological parameters only [24–133], 67 reported results for microbiological and chemical parameters [134–200], 30 reported results for chemical parameters only [201–230], and nine reported results for health outcomes and microbiological parameters [231–239].

As shown in table 1, of the publicly available records which were eligible for inclusion in our review, 84% ($n = 182$) were authored by employees from Chinese government agencies. Among these 182 records, 43% ($n = 78$) were published by authors from various Center for Disease Control and Prevention (CDC) agencies, 29% ($n = 53$) by authors working at government Sanitation and Anti-Epidemic Stations, and 15% ($n = 27$) by authors from Institutes for Health Inspection. Sanitation and Anti-Epidemic Stations were the predecessors for today's China CDC agencies, and Institutes for Health Inspection are affiliated with the China CDC, meaning the vast majority of studies that were eligible for inclusion in our review were conducted and published by authors from China CDC and affiliated agencies.

Across the 216 eligible papers, results from 625 studies were reported (i.e. multiple results reported for parameters based on the analysis of samples collected from different sources and locations). Most studies reported results for water quality parameters in terms of the 'passing rate'; that is, the proportion of samples with test results that were in compliance with the relevant Chinese bottled water standards at the time of the study (the passing rate, '合格率', is a commonly-used metric in China).

Of the papers that reported one or more microbiological outcomes ($n = 186$), only 10% ($n = 18$) provided specific concentrations (e.g. coliform forming units/100 ml). Of the papers that reported one or more chemical outcomes ($n = 97$), 28% ($n = 27$) reported results in terms of specific concentrations (e.g. $mg\,l^{-1}$). In addition to extracting reported data, in cases where sufficient data for passing rates and/or concentrations were reported, we also calculated concentrations and passing rates ourselves (equations for such calculations, along with notes describing where data were found, are embedded in the relevant cells in our SM excel data file available online at stacks.iop.org/ERL/17/013003/mmedia). Summary tables for China's primary bottled water, and drinking water, standards are provided in tables S4 and S5.

We extracted data on the location of the study by province (figure 2) and setting where study samples were collected: rural, urban or peri-urban, or a combination thereof (table 1). The majority

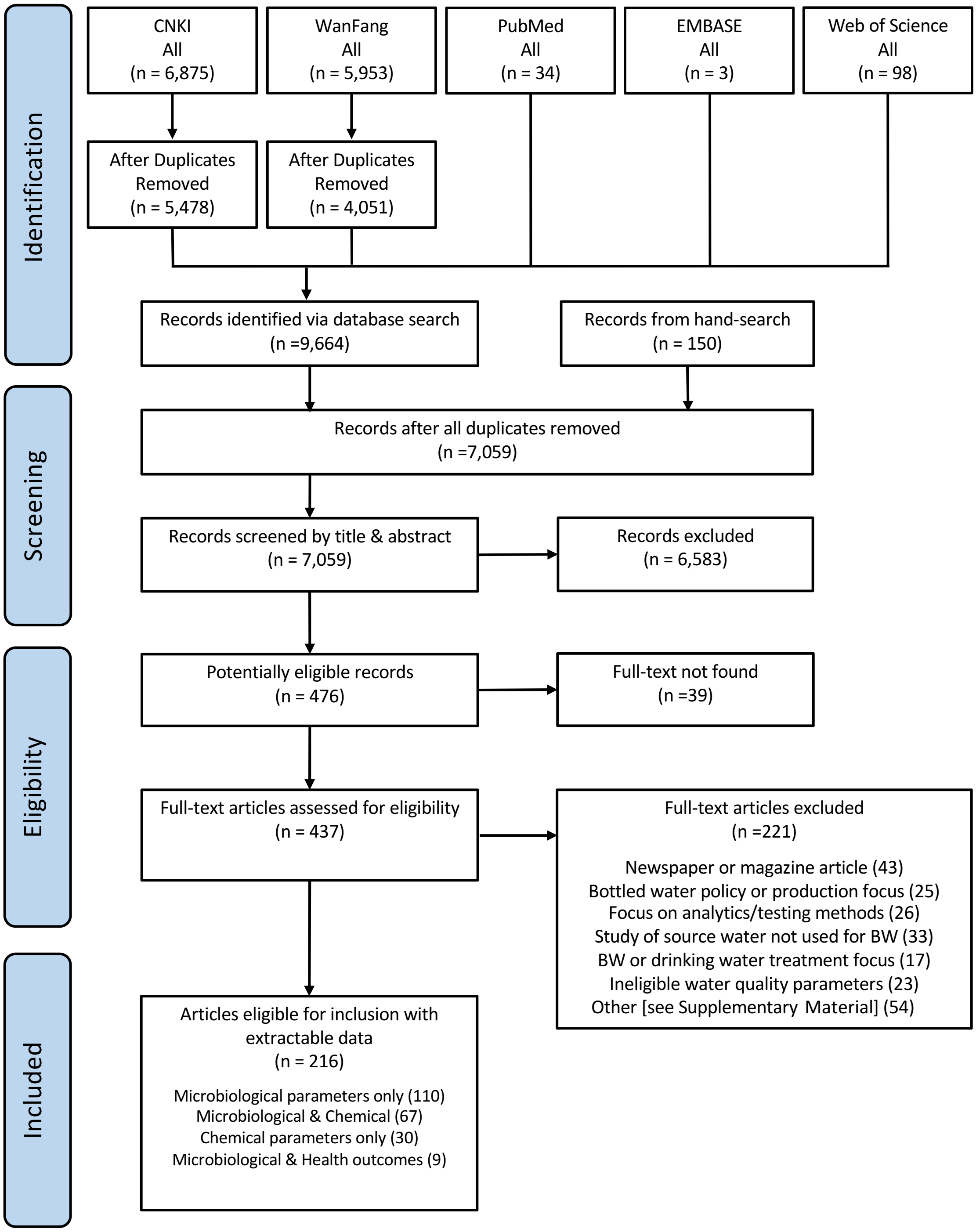

Figure 1. Study screening and selection flow chart.

of studies—overall and by paper type (microbiological, chemical, microbiological and chemical, health outcomes)—were conducted in the relatively higher-income provinces along China's coast (figure 3). We also sought to extract data on the brands of water tested, but this information was provided for only a few studies. Similarly, we attempted to extract data on the method(s) of bottled water treatment used, but only 16 eligible papers provided such information. A histogram of eligible papers by year of publication and paper type is provided in figure S1.

3.3. Microbiological outcomes

Studies that reported results for only microbiological parameters are summarized in table 2, and those that reported results for microbiological and chemical parameters are summarized in table 4. As shown in figure 4, for those studies reporting data for specific pathogens such as Salmonella, Shigella, and Staphylococcus, in almost all cases the samples were reported to be in compliance with China's relevant bottled water standards at the time the studies were conducted (boxplots are shown in figure S2). However, for several indicators of microbiological

Table 1. Overview of eligible records with extractable data.

	Microbiological and chemical (n = 67)		Microbiological only (n = 110)		Chemical only (n = 30)		Health (n = 9)		Total (n = 216)	
	n	%	n	%	n	%	n	%	n	%
Publication language										
Chinese	67	100.0	110	100.0	26	86.7	7	77.8	**210**	**97.2**
English	0	0.0	0	0.0	4	13.3	2	22.2	**6**	**2.8**
Primary author affiliations										
Government agencies	57	85.1	97	88.2	21	70.0	7	77.8	**182**	**84.3**
Universities	7	10.4	8	7.3	6	20.0	0	0.0	**21**	**9.7**
Other (Gov. and Uni., companies)	3	4.5	5	4.5	3	10.0	2	22.2	**13**	**6.0**
Bottled water source										
Retail stores	12	21.1	28	30.4	19	76.0	0	0.0	**59**	**32.2**
Schools and universities	3	5.3	12	13.0	0	0.0	8	88.9	**23**	**12.6**
Bottled water factory	24	42.1	32	34.8	4	16.0	0	0.0	**60**	**32.8**
Retail and bottled water factory	8	14.0	7	7.6	0	0.0	0	0.0	**15**	**8.2**
Other and multiple sources	10	17.6	13	14.1	2	8.0	1	11.1	**26**	**14.2**
Bottled water type/s										
Mineral water (nfs)	24	38.1	45	44.1	15	53.6	2	50.0	**86**	**43.7**
Spring water	2	3.2	3	2.9	1	3.6	1	25.0	**7**	**3.6**
Purified water (nfs)	17	27.0	26	25.5	4	14.3	0	0.0	**47**	**23.9**
Multiple (mixed sources)	11	17.5	9	8.8	2	7.1	0	0.0	**22**	**11.2**
Ambiguous specification	9	14.3	19	18.6	6	21.4	1	25.0	**35**	**17.8**
Season/s study conducted										
Fall	2	5.9	6	12.5	0	0.0	1	11.1	**9**	**9.2**
Winter	1	2.9	2	4.2	1	14.3	2	22.2	**6**	**6.1**
Spring	3	8.8	7	14.6	1	14.3	4	44.4	**15**	**15.3**
Summer	7	20.6	7	14.6	4	57.1	2	22.2	**20**	**20.4**
Multiple	21	61.8	26	54.2	1	14.3	0	0.0	**48**	**49.0**
Study location climate										
Cold/mild temperate	11	16.4	18	16.8	3	10.7	1	11.1	**33**	**15.6**
Warm temperate	17	25.4	31	29.0	11	39.3	1	11.1	**60**	**28.4**
Mild subtropical	26	38.8	40	37.4	8	28.6	6	66.7	**80**	**37.9**
Subtropical/tropical	13	19.4	18	16.8	6	21.4	1	11.1	**38**	**18.0**
Study setting										
Rural	2	3.0	4	3.7	1	3.3	1	12.5	**8**	**3.7**
Urban	30	44.8	68	62.4	19	63.3	7	87.5	**124**	**57.9**
Mixed and other	35	52.2	37	33.9	10	33.3	0	0.0	**82**	**38.3**

Notes: Gov. = government; Uni. = university; BW = bottled water; nfs = not further specified.

contamination, such as total bacteria and total coliforms, many bottles water samples were assessed to exceed the relevant standards (i.e. were not in compliance).

Across microbiological parameters, most studies reported data for total bacteria and total coliforms. As shown in table 3, the mean passing rate from 297 studies of total bacteria was 71.1% (SD = 18.5), and 93.7% (SD = 10.1) for the 241 studies of total coliforms, and 88.9% (SD = 5.8) for the 17 studies of *P. aeruginosa* (see table S6 for unweighted data).

As shown in figure 5, looking at passing rate results by year of study publication, from the late 1990s to late 2000s the mean proportion of samples in compliance increased (improved) slightly for total bacteria. We did not observe evidence of strong temporal trends for total coliforms (publication-specific boxplots for both parameters in figures S3 and S4).

3.4. Chemical outcomes

Studies that reported results for chemical parameters are summarized in tables 4 and 5. Among chemical parameters analyzed, results for lead, arsenic, and nitrite were most commonly reported. Mean passing rates for most parameters were >95% (figure 6 and table 6) though this was not the case for nitrites (mean = 92.6%) or for disinfection byproducts (mean = 71.2%) (boxplots in figure S5 and unweighted data in table S7).

Figure 2. Map of China with number of eligible publications with extractable data by province: all study types. Note: three publications (Wu Q 2009, Xu B 2001, and Zhang Z 2009) reported data from multiple provinces.

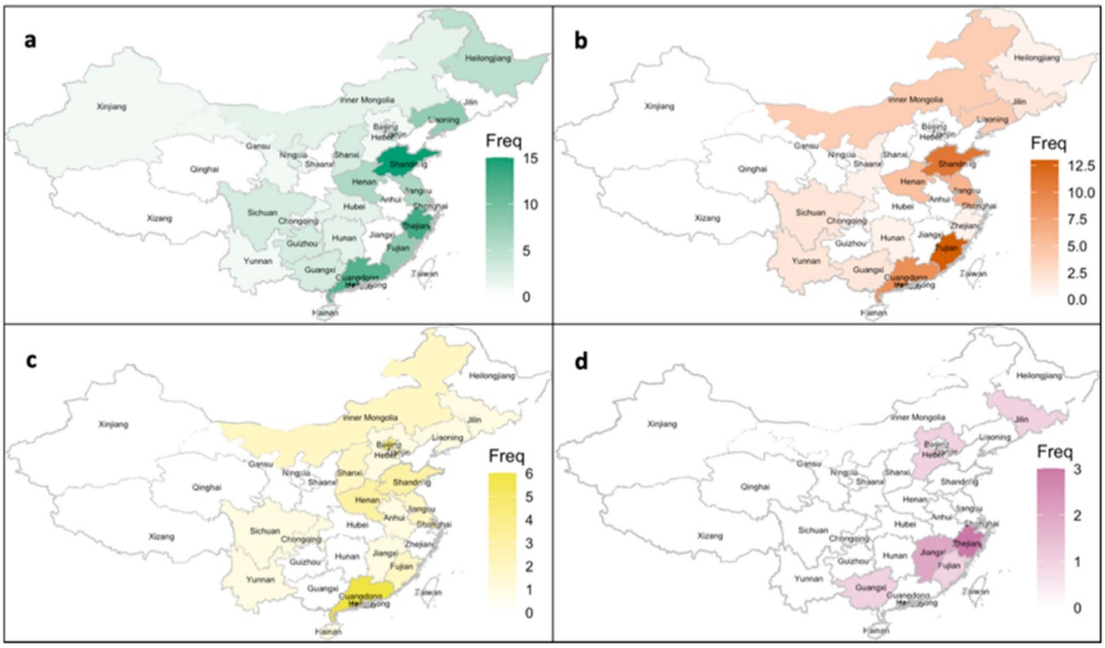

Figure 3. Eligible publications with extractable data by province: microbiological outcomes (a), microbiological and chemical outcomes (b), chemical (c), health outcomes (d). Note: three publications (Wu Q 2009, Xu B 2001, and Zhang Z 2009) reported data from multiple provinces.

Looking at the results from studies that measured nitrite and nitrate by year of study publication (figure 7), there is evidence of a positive trend over most of the time span covered in our review (i.e. studies reported higher average passing rates); the trend is more pronounced for nitrites than for nitrates (publication-specific boxplots in figures S6 and S7).

As discussed previously, relatively few studies reported results in terms of specific concentrations. Across the papers that did report specific concentrations for lead ($n = 8$), cadmium ($n = 3$), arsenic ($n = 5$), and mercury ($n = 3$), aside from one study reporting results for cadmium (Zhou 2016) median concentrations for these heavy metals were all in compliance with China's national bottled

Table 2. Overview of eligible records with microbiological outcomes ($n = 110$).

First author and Pub. year	Province	Season	Microbiological outcome/s
Cai Yitian 1996	Hainan	MD	Total bacteria, total coliforms
Chen Hanwen 2003	Zhejiang	Multiple	Total bacteria
Chen Huixin 2002	Shandong	Multiple	Total coliforms, total bacteria
Chen Lu 2013	Jiangsu	Fall, Winter	Pathogens (multiple/nfs), total bacteria, total coliforms
Chen Shuhu 2014	Henan	MD	*Pseudomonas aeruginosa*, multiple/aggregated organisms
Chen Shuixian 2004	Fujian	Multiple	*P. aeruginosa*
Chen Yijiang 2006	Guizhou	Fall	Total coliforms, total bacteria
Deng Meiqing 2009	MD	MD	*P. aeruginosa*
Duan Guilian 1997	Shandong	MD	Total coliforms, total bacteria
Duan Qiong 2015	Sichuan	MD	Total coliforms, total bacteria
Fan Xuexin 2003	Henan	Winter	Total bacteria, total coliforms
Fan Yi 2010	Chongqing	Multiple	Multiple/aggregated organisms
Fan Zhenhua 2008	Shanxi	MD	Total coliforms, total bacteria, pathogens (multiple/nfs)
Fang Ying 2004	Hunan	Multiple	Total bacteria
Feng Baoling 1995	Guangdong	MD	Total bacteria
Gao Zhixiang 2006	Inner Mongolia	Spring	Total bacteria, multiple/aggregated organisms, total coliforms
Gong Zhimin 2013	Shanghai	MD	Total bacteria, *Staphylococcus aureus*, Salmonella, Shigella, total coliforms
Gu Qiang 2001	Tianjin	Summer	Total coliforms, total bacteria
He Changyun 2001	Guangdong	MD	Total bacteria
He Lianhua 2003	Guangdong	MD	Total coliforms, total bacteria
He Yufang 2007	Zhejiang	MD	Total coliforms, total bacteria, pathogens (multiple/nfs)
Huang Xia 2002	Heilongjiang	Multiple	Total coliforms, pathogens (multiple/nfs), total bacteria
Huang Xuezhen 2001	Guangdong	MD	Total bacteria, total coliforms, pathogens (multiple/nfs)
Jiang Yanwen 2008	Guangdong	MD	Total coliforms, pathogens (multiple/nfs), total bacteria
Jiang Haitang 2015	Guangdong	MD	Total coliforms, total bacteria, fecal indicator bacteria
Jin Yi 2002	Zhejiang	MD	Multiple/aggregated organisms
Ke Qin 1996	Xinjiang	MD	Total coliforms, total bacteria
Li Fei 2013	Guangdong	MD	*Enterococcus faecalis*
Li Fei 2014	Henan	MD	Multiple/aggregated organisms
Li Hong 2002	Fujian	Multiple	Total bacteria
Li Jie 2003	Fujian	Multiple	Multiple/aggregated organisms, pathogens (multiple/nfs), *P. aeruginosa*
Li Qunying 2001	Shandong	MD	Total bacteria

(Continued.)

Table 2. (Continued.)

First author and Pub. year	Province	Season	Microbiological outcome/s
Li Xiaochun 2000	Zhejiang	Multiple	Total coliforms, total bacteria
Li Xiugui 2001	Guangxi	Multiple	Total bacteria
Li Yan 2002	Henan	MD	Total bacteria, total coliforms
Li Yi 2015	Zhejiang	Multiple	*P. aeruginosa*, total bacteria, total coliforms
Lin Guanying 2000	Fujian	MD	Total bacteria
Lin Jian 2001	Fujian	MD	Total coliforms, total bacteria, multiple/aggregated organisms
Lin Xiangchun 2013	Guangdong	MD	Multiple/aggregated organisms
Liu Cang 2014	Zhejiang	Multiple	Total coliforms, *P. aeruginosa*, total bacteria
Liu Chengxiang 2009	Jiangsu	MD	Total bacteria, total coliforms
Liu Jinghua 2001	Tianjin	Spring	Total coliforms, total bacteria, pathogens (multiple/nfs)
Liu Shiming 2014	Hubei	MD	Multiple/aggregated organisms
Liu Shu 2001	Jiangsu	Fall	Total bacteria, total coliforms
Liu Xiangjing 2005	Sichuan	MD	Total bacteria, total coliforms
Liu Yacui 2004	Shandong	MD	Total bacteria, total coliforms
Liu Yinghang 2013	Guangdong	Multiple	Total bacteria, total coliforms
Liu Yongui 1999	Shandong	Multiple	Total bacteria, total coliforms
Long Wenfang 2012	Hainan	MD	Total bacteria, total coliforms, fecal indicator bacteria
Lu Juan 2004	Jiangsu	MD	Total bacteria, total coliforms
Lu Qian 1995	Beijing	Summer	Total coliforms, total bacteria, *P. aeruginosa*
Lun Lufang 2002	Fujian	Fall	Total coliforms, total bacteria
Ma Qunfei 2000	Fujian	MD	Total coliforms, total bacteria
Mu Zhenguo 2003	Hebei	Spring	Total bacteria
Pan Huiming 2008	Shanghai	Summer	Total bacteria, fecal indicator bacteria, total coliforms
Pan Lizhen 2008	Jiangsu	MD	Multiple/aggregated organisms
Qu Lianzhao 2015	Guangdong	MD	Multiple/aggregated organisms
Ren Cong 2005	Shandong	MD	Total coliforms, total bacteria
Ren Liju 2001	Shandong	MD	Multiple/aggregated organisms, total coliforms
Sao Peilan 1995	Ningxia	Multiple	Total coliforms, pathogens (multiple/nfs), total bacteria
Shao Kun 2011	Shandong	MD	Total coliforms, total bacteria
Shao Peilan 1997	Ningxia	Multiple	Total bacteria, total coliforms
Shen Mingxia 2004	Guizhou	MD	Total bacteria, total coliforms
Shen Qiuju 2004	Shandong	MD	Total bacteria

(Continued.)

Table 2. (Continued.)

First author and Pub. year	Province	Season	Microbiological outcome/s
Sheng Yunling 2014	Shandong	Fall	Total coliforms, total bacteria
Si Guojing 2005	Zhejiang	MD	Total bacteria, pathogens (multiple/nfs), total coliforms
Su Ping 2003	Liaoning	MD	Multiple/aggregated organisms
Su Zhitai 2014	Fujian	MD	Total coliforms, total bacteria
Sun Kejiang 2001	Tianjin	Spring	Multiple/aggregated organisms
Sun Xianlu 2009	Henan	Multiple	Pathogens (multiple/nfs), total bacteria, total coliforms
Wang Benli 2013	Shandong	Summer	Multiple/aggregated organisms
Wang Fengyun 2004	Shandong	Summer	Total coliforms, total bacteria
Wang Hongling 1998	Zhejiang	Multiple	Total coliforms, total bacteria
Wang Huijun 2010	Heilongjiang	MD	Total bacteria, total coliforms, pathogens (multiple/nfs)
Wang Jingbo 2002	Shandong	Multiple	Total bacteria, total coliforms
Wang Riwei 2012	Shanxi	Fall	Total bacteria, pathogens (multiple/nfs), total coliforms
Wang Tianhui 2007	Shanxi	Spring	Total coliforms, pathogens (multiple/nfs), total bacteria
Wang Xiaodong 2005	Hubei	MD	Total bacteria, total coliforms
Wang Yuanping 2014	Tianjin	MD	Total coliforms, fecal indicator bacteria, total bacteria, pathogens (multiple/nfs)
Wei Hongzhen 2014	Guangxi	MD	*S. aureus*, Shigella, Salmonella, total coliforms, total bacteria
Wen Ping 2005	Liaoning	Multiple	Total coliforms, total bacteria
Wen Tao 2003	Liaoning	MD	Total coliforms, total bacteria
Wen Rui 2011	Heilongjiang	Summer	Total bacteria, multiple/aggregated organisms, total coliforms
Wu Xiaofang 2007	Zhejiang	MD	Total bacteria, total coliforms
Xie Lijian 2004	Jiangsu	Multiple	Total bacteria, total coliforms, pathogens (multiple/nfs)
Xu Bin 2009	Zhejiang	MD	Salmonella, Shigella, total coliforms, *S. aureus*, total bacteria
Xu Bing 2001	Multiple[a]	Multiple	Multiple/aggregated organisms ([a]multiple = Beijing, Tianjin, Shanghai, Sichuan)
Xu Jingye 2004	Zhejiang	Multiple	Total coliforms, total bacteria
Xu Ke 2008	Inner Mongolia	MD	Total coliforms, total bacteria
Yan Yong 2002	Zhejiang	MD	Total bacteria, pathogens (multiple/nfs), total coliforms
Yang Aiping 2003	Shandong	MD	Total bacteria
Yang Shuqing 2005	Zhejiang	Fall	Total bacteria, pathogens (multiple/nfs), total coliforms
Yang Yuzhi 1996	Beijing	MD	Total bacteria
Yang Zhongli 2004	Yunnan	MD	Multiple/aggregated organisms
Yao Yi 2003	Liaoning	MD	Total bacteria

(Continued.)

Table 2. (Continued.)

First author and Pub. year	Province	Season	Microbiological outcome/s
Yu Chunhui 2002	Shandong	Spring	Multiple/aggregated organisms, *P. aeruginosa*, pathogens (multiple/nfs)
Zeng Aihua 2012	Guangdong	Multiple	Viral pathogens
Zeng Changying 2003	Sichuan	MD	Total coliforms, total bacteria
Zhang Jian 2004	Guangdong	Spring	Total bacteria, total coliforms
Zhang Jianhua 2000	Henan	MD	Total bacteria, total coliforms
Zhang Lixin 2003	Heilongjiang	MD	Total bacteria, total coliforms
Zhang Weina 2015	Heilongjiang	Multiple	Multiple/aggregated organisms
Zhang Zhaoqiang 2004	Hunan	MD	Multiple/aggregated organisms
Zhang Zhiyi 2009	Multiple[b]	Summer	Protozoal pathogens ([b]multiple = Liaoning and Tianjin)
Zhao Hong 2005	Liaoning	Multiple	Total bacteria, total coliforms
Zhao Hui 1996	Gansu	MD	Pathogens (multiple/nfs)
Zhao Yong 2008	Liaoning	Multiple	Total coliforms, total bacteria
Zhen Honghui 1999	Guangxi	MD	Total coliforms, total bacteria
Zheng Yumei 2002	Guizhou	MD	Total bacteria, total coliforms
Zhou Shuangqiao 2002	Liaoning	MD	Total bacteria

Notes: nfs = not further specified; MD = missing data.

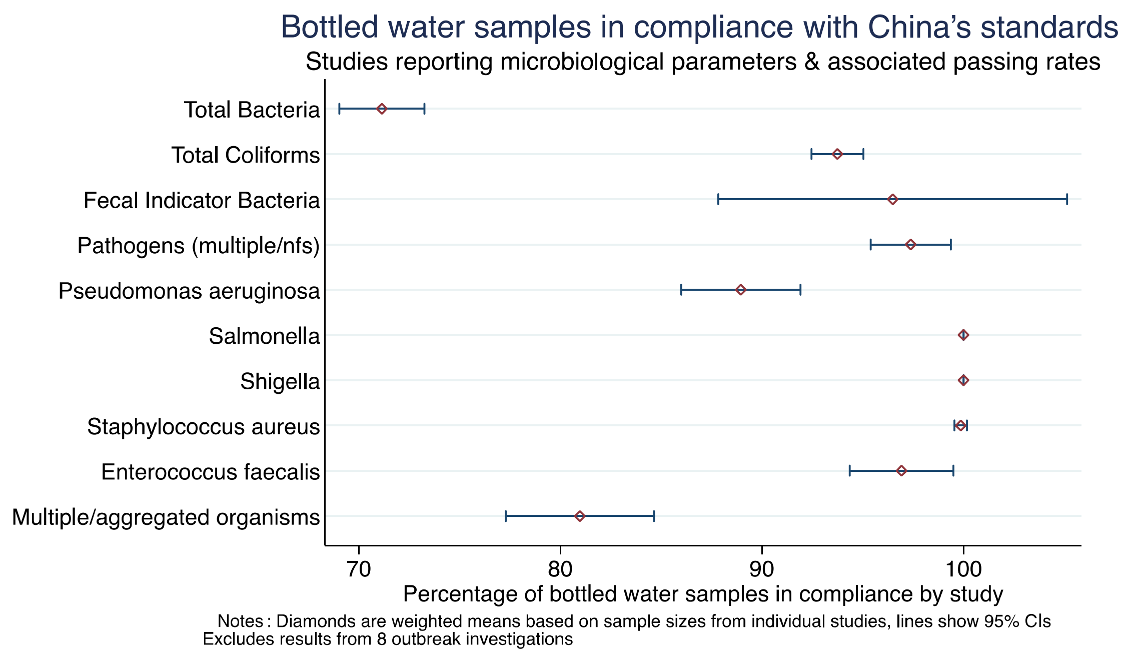

Figure 4. Passing rate means and 95% confidence intervals (CI) for selected microbiological parameters.

Table 3. Summary statistics for reported passing rates for selected microbiological parameters.

	Passing rate (as a percentage):			Data aggregated from:	
	Median	Mean	SD of mean	Total studies	Total samples
Total bacteria	75.3	71.1	18.5	297	28 109
Total coliforms	98.7	93.7	10.1	241	24 585
Fecal indicator bacteria[a]	100	96.5	8.2	6	543
Pathogens (multiple/nfs)[a]	100	97.4	8.7	76	4617
P. aeruginosa	91.4	88.9	5.8	17	4815
Salmonella	100	100	0	14	725
Shigella	100	100	0	14	725
S. aureus	100	99.9	0.5	14	725
E. faecalis	100	96.9	3.6	10	130
Multiple/aggregated organisms[a]	88.9	81.0	19.2	107	7077

Notes: nfs = not further specified. Statistics weighted by study sample sizes. Excludes results from eight publications reporting results from outbreak investigations.

[a] Study authors reported aggregated results using this classification, with insufficient available data to extract 'passing rate' results for specific organisms.

water standards (figure 8) (additional details in table S4).

3.5. Health outcomes

Studies that reported results for health outcomes and microbiological parameters are summarized in table 7. Eight of the nine studies which reported data for health outcomes were outbreak investigations, and of those, only four (case-control study designs) reported sufficient data for comparative analysis. As shown in figure 9, across these four case-control outbreak investigations, consumption of bottled water was significantly associated with an increase in the pooled odds of reported gastrointestinal illness (logged OR = 1.90, $p < 0.001$). However, because these investigations were conducted in response to disease outbreaks, and focused on student populations, the results are not generalizable to more typical situations and settings.

Funnel plot asymmetry indicated some evidence of potential publication bias (see figure S8). It is reasonable to assume that similar case-control studies with null findings may have been conducted over this time period, but were perhaps not submitted for publication. More broadly, the nature of these studies limits our ability to generalize beyond outbreak settings.

3.6. Meta-regression

As shown in table 8, results from meta-regression analyses indicated that, after controlling for other variables in the models, reported passing rates for microbiological and chemical outcomes were positively associated with the year of study publication,

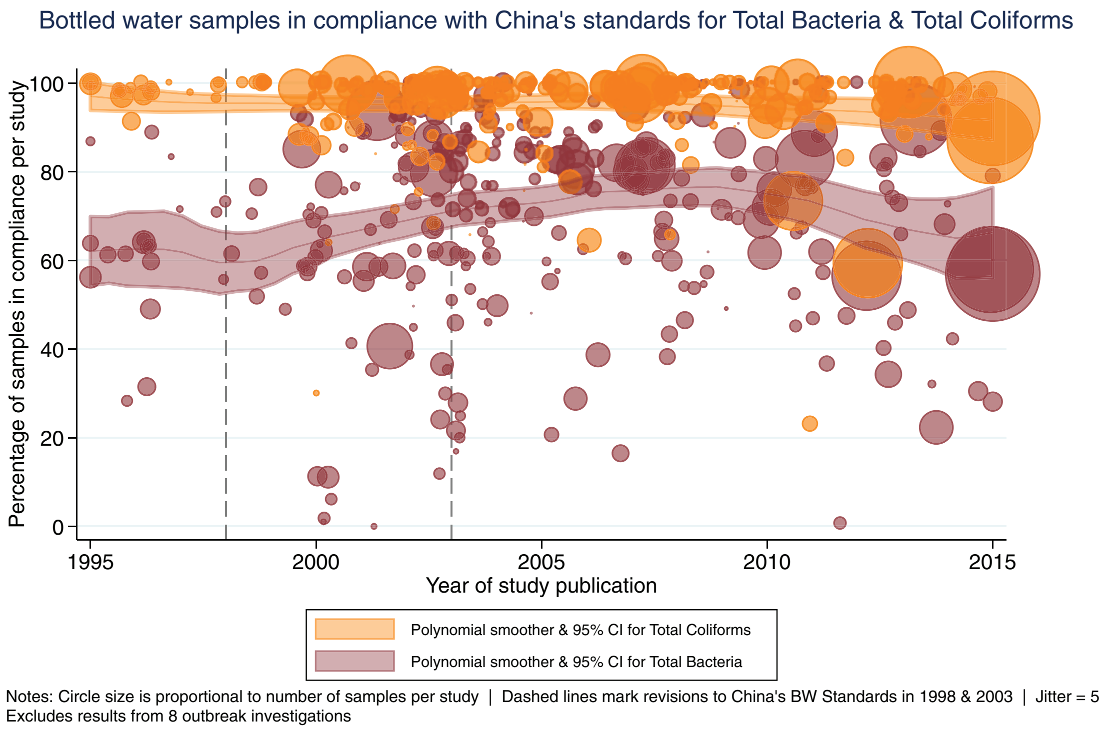

Figure 5. Samples in compliance for total bacteria and total coliforms by publication years.

though the association was only statistically significant for microbiological outcomes, and not for chemical outcomes ($p = 0.017$ and $p = 0.115$, respectively) (model-predicted passing rates for both outcomes in figures S9 and S10). Reported passing rates were significantly lower (i.e. worse) for studies conducted in rural regions compared with urban and other settings, for both microbiological and chemical outcomes ($p = 0.041$ and $p = 0.002$, respectively); however, relatively few studies ($n = 13$ and $n = 2$, respectively) were conducted in primarily rural settings (table S8).

4. Discussion

4.1. Results in context: climate and economic indicators

We observed some evidence of differences in mean passing rates for microbiological outcomes, but not for chemical outcomes, by climatic region (table 9 and figure S11). This observation of higher overall passing rates in warmer and wetter regions (i.e. more samples found to be in compliance compared with cold/mild and warm regions) is potentially at odds with previous drinking-water focused research which found higher overall prevalence of fecal indicator organisms in wetter and warmer conditions [240]; though this would likely depend, among other factors, on bottled water storage durations prior to testing (and we lacked the data needed to evaluate this potential association).

To evaluate the potential impacts of broader economic indicators and socioeconomic status by study setting, we used 2012 Household Consumption Expenditure data from China's National Bureau of Statistics [241] as a comparative indicator of economic status by province. After sorting provinces into thirds based on this expenditure data, we observe that for microbiological outcomes the mean passing rate from studies conducted in provinces with lower annual consumption expenditures (RMB 8–15 $\times$ 10^7) was significantly lower compared with the mean from provinces with higher (RMB $> 20 \times 10^7$) consumption expenditures (80.1% and 86.8%, respectively; ANOVA, using analytic weights based on sample size, Scheffe's test, $p < 0.001$). No significant differences in passing rates by levels of consumption expenditures were observed for chemical outcome data (table S9). However, after controlling for other covariates in our meta-regression models (table 8), we did not observe any significant associations between these economic indicators and overall passing rates.

4.2. Results in context: bottled water characteristics

Compared with mineral, spring, and other types of bottled water, results from the meta-regression show that passing rates were higher for samples from 'purified' bottled water, and the associations were statistically significant for both microbiological and chemical outcomes ($p = 0.021$ and $p = 0.014$, respectively). However, bivariate analysis of passing rates and

Table 4. Overview of eligible records with microbiological and chemical outcomes ($n = 67$).

First author and publication year	Province	Season	Microbiological outcome/s	Chemical outcome/s
Ao Zhixiong 2003	Fujian	Summer	Total bacteria	Nitrite
Cao Changhui 2006	Shandong	Summer	Total bacteria	Nitrite
Cui Xiangshu 2011	Jilin	MD	Total bacteria, total coliforms	Nitrate, fluoride, other heavy metals
Dou Caihong 2010	Liaoning	Multiple	Multiple/aggregated organisms	Multiple parameters
Gao Ruiyun 2011	Shandong	MD	Total coliforms, total bacteria, pathogens (multiple/nfs), multiple/aggregated organisms	Arsenic, lead, nitrate, other heavy metals, fluoride, trichloromethane (chloroform), cadmium
Ge Limin 2005	Liaoning	MD	Total coliforms, total bacteria, Pathogens (multiple/nfs)	Nitrite, alkali/alkaline earth metals
Gong Yiyuan 2008	Sichuan	Multiple	Total coliforms, total bacteria, Salmonella, *S. aureus*, Shigella	Nitrite, arsenic, chlorine (nfs), other heavy metals
He Wujun 2000	Jiangsu	Multiple	Total coliforms, total bacteria, pathogens (multiple/nfs)	Nitrite, lead, arsenic
Huang Yuanxin 1995	Guangxi	Summer	Total coliforms, total bacteria, pathogens (multiple/nfs)	Lead, arsenic, other heavy metals
Jiang Yonghong 2000	Guangxi	Multiple	Total bacteria	Nitrite, chlorine (nfs), lead, arsenic, other heavy metals, trichloromethane (chloroform), carbon tetrachloride
Kang Fengchun 2014	Shandong	Multiple	Total bacteria	Other
Li Caixian 2003	Guangdong	MD	Total bacteria, total coliforms	Nitrite, lead, volatile phenols, other heavy metals
Li Jing 2008	Liaoning	Multiple	Total bacteria, total coliforms	Nitrite
Li Ruiying 1996	Shandong	Multiple	Total bacteria, total coliforms, Salmonella, Shigella, *S. aureus*	Arsenic, lead, nitrate, nitrite, other heavy metals
Li Ruiying 2003	Shandong	MD	Total bacteria, total coliforms	Nitrate
Liang Yongzhu 2003	Shandong	Multiple	Total bacteria, total coliforms	Nitrite, lead, arsenic, other heavy metals
Lin Meiyan 2005	Fujian	MD	Total bacteria, total coliforms, pathogens (multiple/nfs), multiple/aggregated organisms	Multiple parameters
Lin Meiyan 2009	Fujian	MD	Multiple/aggregated organisms	Multiple parameters
Lin Shengqing 1996	Fujian	MD	Total bacteria, total coliforms	Nitrite
Lin Xiaohong 2010	Fujian	Winter	Total bacteria, total coliforms	Nitrite, ammoniacal nitrogen
Lin Xijian 2003	Hunan	Fall	Total bacteria, total coliforms	Nitrate
Lin Yizhi 2011	Guangdong	Summer	Total coliforms, multiple/aggregated organisms	Chlorine (nfs)

(Continued.)

Table 4. (Continued.)

First author and publication year	Province	Season	Microbiological outcome/s	Chemical outcome/s
Liu Maoqiang 2013	Shandong	MD	Total bacteria, total coliforms, multiple/aggregated organisms	Nitrite, nitrate
Liu Meiqin 2012	Shandong	Multiple	Multiple/aggregated organisms	Nitrate, chlorine (nfs)
Liu Ruqing 2003	Guangdong	Spring	Total bacteria	Nitrite
Liu Shaojun 2006	Fujian	MD	Total bacteria, total coliforms	Nitrate
Liu Suyi 2003	Fujian	Multiple	Total bacteria, total coliforms, fecal indicator bacteria, Pathogens (multiple/nfs)	Nitrate, nitrite, arsenic, lead, mercury, cadmium, chlorine (nfs), fluoride, other heavy metals
Liu Xuehua 2001	Shandong	Spring	Total coliforms, total bacteria	Lead, chlorine (nfs), nitrite
Ma Liangcai 2000	Jiangsu	Multiple	Total bacteria, total coliforms	Lead, arsenic, trichloromethane (chloroform), other heavy metals, carbon tetrachloride
Ma Qunfei 2001	Fujian	MD	Total coliforms, total bacteria	Nitrite
Ma Qunfei 2002	Fujian	MD	Total coliforms, total bacteria	Nitrite
Mou Sheng 2001	Yunnan	MD	Multiple/aggregated organisms	Other
Niu Zhirui 2013	Shaanxi	MD	Total coliforms	Nitrite
Peng Jingxian 2008	Inner Mongolia	MD	Total coliforms	Lead, arsenic, cyanide, trichloromethane (chloroform), carbon tetrachloride, volatile phenols, other heavy metals
Peng Shasha 2004	Henan	MD	Total coliforms, total bacteria, Pathogens (multiple/nfs)	Lead, arsenic, cyanide, carbon tetrachloride, trichloromethane (chloroform), chlorine (nfs), volatile phenols, other heavy metals
Sha Jihui 2007	Fujian	MD	Total coliforms, total bacteria	Nitrite
Sun Liping 2009 A	Inner Mongolia	MD	Total bacteria, pathogens (multiple/nfs)	Nitrite, arsenic, lead, other heavy metals
Sun Yang 2001	Guangdong	Multiple	Total bacteria, total coliforms	Lead, arsenic, cyanide, trichloromethane (chloroform), carbon tetrachloride, chlorine (nfs), volatile phenols, nitrite, other heavy metals
Wang Dailiang 2013	Sichuan	Multiple	Total bacteria, total coliforms	Multiple parameters
Wang Guangxu 2009	Liaoning	MD	Total bacteria, total coliforms	Alkali/alkaline earth metals
Wang Liping 2000	Jiangsu	MD	Total bacteria, total coliforms	Nitrite, volatile phenols, cyanide
Wang Lishen 2010	Guangdong	MD	Total coliforms, total bacteria	Lead, arsenic, mercury, various light metals, other heavy metals
Wang Mingzhu 1999	Shandong	MD	Total bacteria, total coliforms	Arsenic, nitrite, lead, other heavy metals
Wang Shuyuan 2003	Yunnan	Multiple	Total bacteria, total coliforms	Arsenic, lead, other heavy metals, nitrite
Wang Xiaofeng 2007	Jiangsu	MD	Total coliforms, total bacteria, pathogens (multiple/nfs)	Nitrate, chlorine (nfs)

(Continued.)

Table 4. (Continued.)

First author and publication year	Province	Season	Microbiological outcome/s	Chemical outcome/s
Wang Yan 2002	Heilongjiang	Summer	Total coliforms, total bacteria	Lead, nitrate, arsenic, other heavy metals
Wang Yumei 2011	Inner Mongolia	MD	Total bacteria, *S. aureus*, total coliforms, Salmonella, Shigella	Volatile phenols, nitrite
Wang Zhengzhi 2015	Jilin	MD	Total coliforms, total bacteria	Nitrate, lead
Wu Hongmei 2003A	Henan	Multiple	Total bacteria, total coliforms	Arsenic, nitrate, nitrite, cyanide, fluoride, cadmium, lead, other heavy metals
Wu Hongmei 2003B	Henan	Multiple	Total bacteria, total coliforms, pathogens (multiple/nfs)	Arsenic, lead, nitrite
Wu Huigang 2002	Guangdong	MD	Total bacteria, total coliforms, pathogens (multiple/nfs)	Arsenic, mercury, lead, cyanide, volatile phenols, fluoride, nitrite, other heavy metals, chlorine (nfs), cadmium
Ying Liang 2007	Shanghai	MD	Total bacteria	Lead, carbon tetrachloride, trichloromethane (chloroform)
Yu Peng 2009	Shandong	Summer	Total coliforms, total bacteria, Salmonella, Shigella, *S. aureus*	Arsenic, nitrite
Yuan Ping 2011	Henan	MD	Total bacteria, total coliforms	Nitrate, lead
Zhang Guanfeng 2006	Guangdong	Spring	Total bacteria, pathogens (multiple/nfs)	Nitrate, arsenic, carbon tetrachloride, trichloromethane (chloroform), lead, other heavy metals
Zhang Runsheng 2013	Inner Mongolia	Multiple	Total bacteria, total coliforms	Arsenic, lead, other heavy metals
Zhang Weina 2012	Henan	Multiple	Total bacteria, total coliforms	Nitrite, lead, arsenic, other heavy metals
Zhang Xiaodan 2013	Shanghai	Multiple	Total bacteria, total coliforms	Other
Zhang Yongqing 2012	Guangdong	Multiple	*P. aeruginosa*	Disinfectant byproducts
Zhen Yin 2004	Jiangsu	Fall	Total bacteria, total coliforms	Nitrite, chlorine (nfs)
Zheng Daikun 2002	Chongqing	MD	Multiple/aggregated organisms	Nitrate, cyanide, alkali/alkaline earth metals
Zheng Xiaoyan 1998	Fujian	Summer	Total bacteria, total coliforms, pathogens (multiple/nfs)	Nitrite
Zheng Xiaoyan 1999	Fujian	MD	Total bacteria, multiple/aggregated organisms	Multiple parameters
Zhou Lubin 2010	Fujian	MD	Total coliforms, total bacteria, Salmonella, *S. aureus*, Shigella	Lead, arsenic, nitrite
Zhou Xiaohong 2011	Zhejiang	MD	Total bacteria, total coliforms, pathogens (multiple/nfs)	Lead, arsenic, nitrite, other heavy metals
Zhu Jiawen 2005	Jiangsu	Multiple	Total bacteria	Chlorine (nfs), nitrite
Zhu Xiaohui 2013	Guangdong	MD	Total coliforms, total bacteria, fecal indicator bacteria	Various light metals, other heavy metals

Notes: nfs = not further specified; MD = missing data.

Table 5. Overview of eligible records with chemical and related outcomes ($n = 30$).

First author and publication year	Province	Season	Chemical and related outcome/s
Chen Tao 2014	Beijing	MD	Radiation (alpha, beta, other)
Gao Xue 2015	Hebei	MD	Organic chlorine pesticides
Guo Yicao 1999	Guangdong	MD	Radiation (alpha, beta, other)
Huang Yeru 1999	Beijing	MD	Benzene, trichloromethane (chloroform)
Jing Yanyan 2015	Beijing	Summer	Cyanide, lead, volatile phenols, ammoniacal nitrogen, nitrate, cadmium, fluoride, arsenic, mercury, other heavy metals
Lan Zhongzhou 2002	Shandong	MD	Nitrite
Li Jian 2008	Jiangsu	Multiple	Lead, other heavy metals, various light metals, alkali/alkaline earth metals, cadmium
Li Jun 2014	MD	MD	Organophosphate flame retardants
Li Xu 2010	Guangdong	MD	Phenols
Liang Wei 2012	Jiangsu	MD	Disinfection byproducts
Lin Guocan 2013	Fujian	MD	Radiation (alpha, beta, other)
Lin Lixiong 2010	Guangdong	MD	Radiation (alpha, beta, other)
Lin Yuna 2009	Guangdong	MD	Disinfection byproducts
Lin Zhi 1995	Hainan	MD	Radiation (alpha, beta, other)
Ma Wei 2004	Tianjin	MD	Fluoride
Song Chunmei 2012	Jilin	MD	Nitrite
Sun Lili 2004	Guangdong	MD	Fluoride
Sun Liping 2009B	Inner Mongolia	MD	Other
Tong Jun 2009	Shanghai	MD	Disinfection byproducts
Wang Hexing 2012	Shanghai	Summer	Phenols
Wang Xiaoting 2015	Shanxi	MD	Volatile organic compounds (VOCs), trichloromethane (chloroform), benzene
Wu Li 1998	Henan	MD	Radiation (alpha, beta, other)
Wu Qian 2010	Multiple[a]	Winter	Perchlorate ([a]multiple = Shandong, Liaoning, Shanghai, Henan, Beijing, Yunnan, Tianjin, Jiangxi, Sichuan, Shanxi, Guangdong)
Xu Hongyin 2015	Inner Mongolia	MD	Disinfection byproducts
Xu Renji 2010	MD	MD	Alkali/alkaline earth metals
Xu Zhengsheng 2012	Anhui	Summer	Benzene, trichloromethane (chloroform)
Zeng Zhiding 2011	Fujian	MD	Arsenic, nitrite, other
Zhang Shufang 2009	Henan	Summer	Disinfection byproducts
Zhou You 2016	Chongqing	MD	Lead, cadmium, other heavy metals, arsenic, mercury
Zhuang Guidong 1997	Shandong	Spring	Nitrite

Note: MD = missing data.

bottled water type did not indicate substantive differences in this regard (see table S10).

With regard to the size of the water bottles sampled, we did not observe any significant differences in mean passing rates for chemical outcomes and bottle size (table 10). However, for studies reporting microbiological outcomes based on samples from smaller water bottles (<2 l), the mean passing rate (72.1%) was more than 10% points lower than the mean passing rate (83.4%) from studies of larger water bottles (>10 l) (Analysis of variance [ANOVA], using analytic weights based on sample size, Scheffe's test, $p < 0.001$ for comparison between small and large categories).

Looking at only those studies that reported results for total coliforms (table 10), we see that the mean passing rate is also significantly lower for small bottles compared with larger ones (ANOVA, using analytic weights based on sample size, Scheffe's test, $p < 0.001$ for comparison between small and large categories). These findings with regard to small versus large bottles and microbiological passing rates are somewhat at odds with previous research (outside of China) which found more evidence of microbiological contamination in larger water bottles [12]. Whereas 131 papers reported the size of the water bottles sampled in qualitative terms (e.g. 'small', 'large'), only 21 papers reported the specific size of the bottles in number of liters. For those papers ($n = 21$), the data are suggestive of higher levels of microbiological contamination (i.e. lower passing rates) in larger bottles, but the differences between smaller bottles (<1 l) and large (∼19 l) was not significant (see figure S12). With regard to contamination and risks of exposure associated with the use of small- or large-sized bottles, most Chinese households who use large water bottles heat or boil the water before consuming it, a practice that would be expected to reduce pathogen exposure [22, 242]; this is not typically the case with small, single-use, water bottles. That

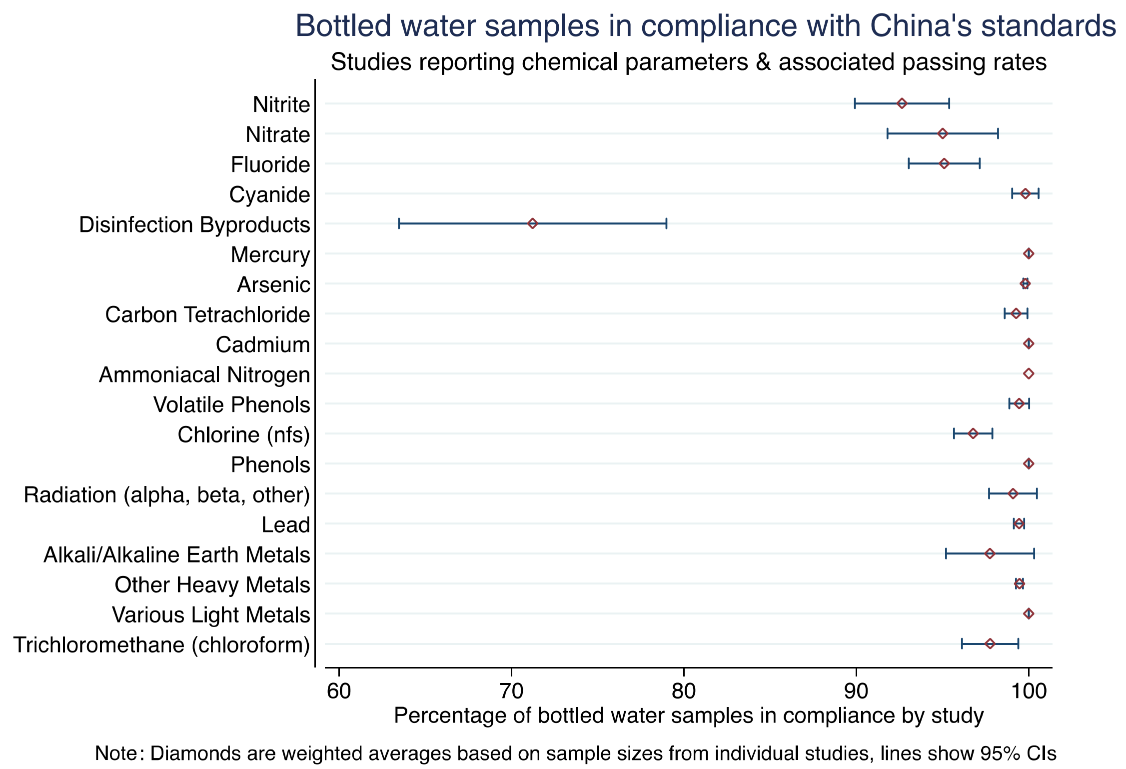

Figure 6. Passing rate means and 95% confidence intervals (CI) for selected chemical parameters.

Table 6. Summary statistics for reported passing rates for selected chemical parameters.

	Passing rate (as a percentage):			Data aggregated from:	
	Median	Mean	SD of mean	Total studies	Total samples
Nitrite	97.6	92.6	12.7	85	7261
Nitrate	97.3	95	8.6	30	2361
Fluoride	91.6	95.1	4	17	1589
Cyanide	100	99.8	1.3	13	1019
Disinfection byproducts[a]	57.9	71.2	17.9	23	973
Mercury	100	100	0	7	253
Arsenic	100	99.8	0.4	49	4525
Carbon tetrachloride	99.6	99.3	0.7	7	1108
Cadmium	100	100	0	11	521
Ammoniacal nitrogen	100	100	.	1	18
Volatile phenols	100	99.4	0.9	11	1236
Chlorine (nfs)	96.6	96.8	2.2	18	1828
Phenols	100	100	0	3	63
Radiation (alpha, beta, other)	99.7	99.1	1.7	8	1292
Lead	100	99.4	1.1	52	4880
Other heavy metals	100	99.5	1.1	122	8786
Various light metals	100	100	0	9	338
Trichloromethane (chloroform)	97.7	97.8	1.9	8	1197

Notes: nfs = not further specified. Statistics weighted by study sample sizes.
[a] Study authors reported aggregated results using this classification, with insufficient available data to extract 'passing rate' results for specific organisms or indicators.

said, because larger bottles are not typically consumed immediately after being opened, consumption over a period of days or weeks could provide more time for organism growth if the bottled water was already contaminated when purchased, or became so after the bottle was opened. Overall then, we cannot draw clear conclusions from these data with respect to relationships between bottled water size and reported passing rates.

4.3. Methodological rigor and risk of bias analysis

Studies were assigned an ROB score based on six items (table S2) and were then divided into thirds and assigned to groups for low, medium, and high ROB

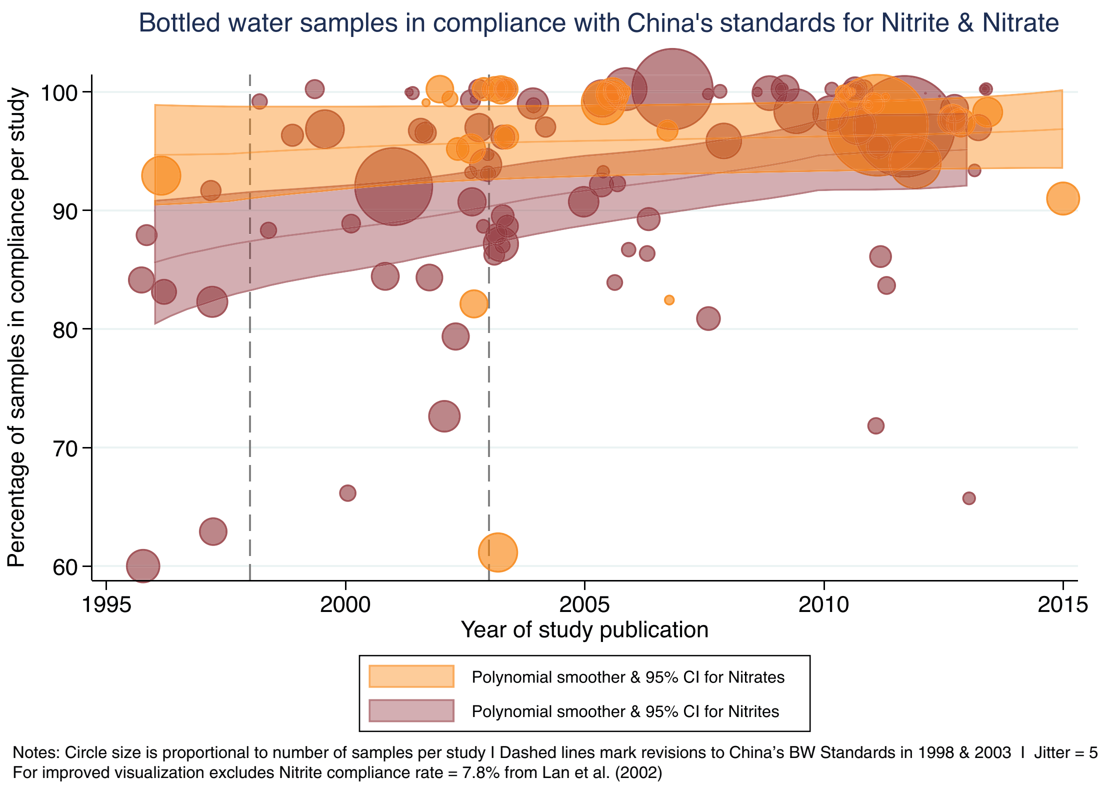

Figure 7. Samples in compliance for nitrate and nitrite by publication year.

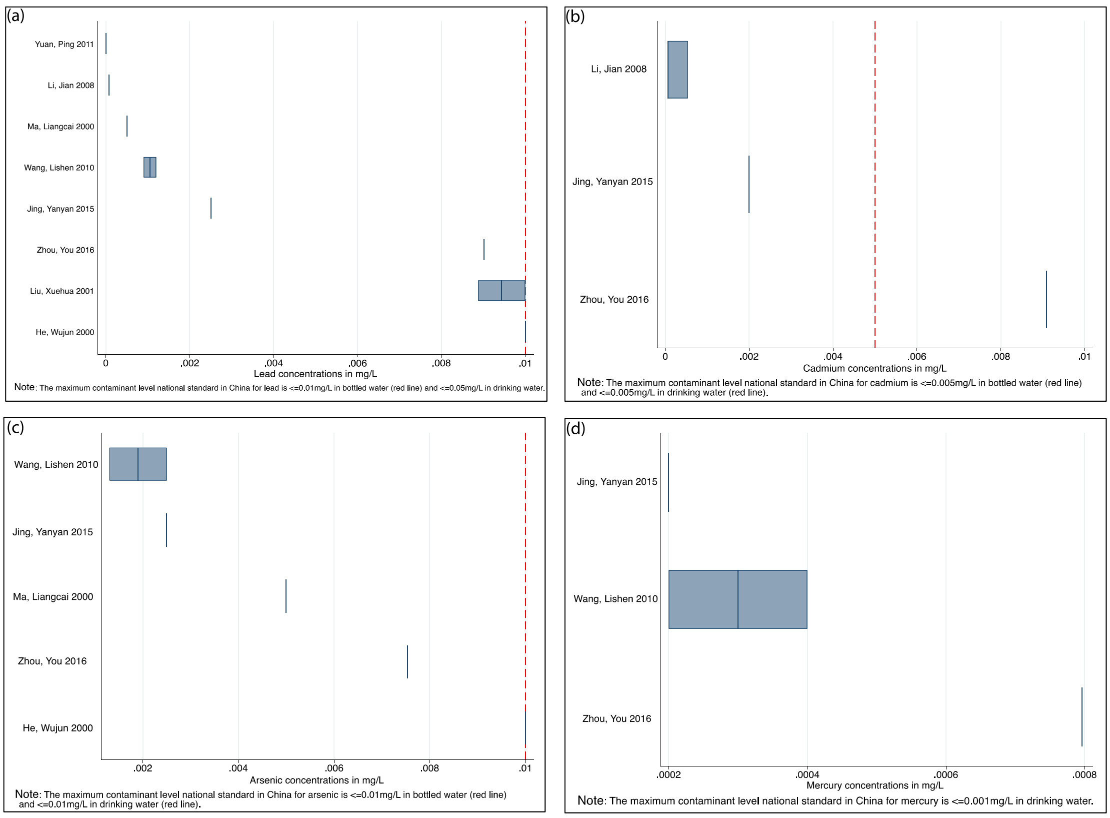

Figure 8. Boxplots of reported concentrations by study for lead (a), cadmium (b), arsenic (c), and mercury (d), with references to China's national maximum contaminant standards for bottled water (GB19298-2003) (red dashed lines) (additional details in table S4).

Table 7. Overview of eligible records with health and microbiological outcomes ($n = 9$).

First author and publication year	Province	Season	Study type/design	Health outcome	Microbiological outcome/s
Cohen Alasdair 2015	Guangxi	Summer	Observational/cross-sectional	Gastroenteritis (diarrhea)	Fecal indicator bacteria (thermotolerant coliforms)
Liu Li 2008	Jilin	Summer	Outbreak/unclear	Gastroenteritis	Total bacteria, pathogenic bacteria (nfs), total coliforms
Shen Jichuan 2011	Zhejiang	Spring	Outbreak/case-control	Gastroenteritis	Total coliforms, norovirus, total bacteria
Song Jianqiang 2015	Zhejiang	Winter	Outbreak/unclear	Gastroenteritis (norovirus)	Total coliforms, norovirus, total bacteria
Song Jie 2014	Hebei	Spring	Outbreak/unclear	Gastroenteritis (norovirus)	Total bacteria, total coliforms, norovirus
Wang Jie 2015	Zhejiang	Winter	Outbreak/case-control	Gastroenteritis (norovirus)	Total bacteria, norovirus
Wang Ruiping 2012	Jiangxi	Spring	Outbreak/case-control	Gastroenteritis	Total coliforms, *Escherichia coli*, total bacteria
Wu Wei 2014	Jiangxi	Spring	Outbreak/case-control	Gastroenteritis	Enterovirus, total coliforms, calicivirus, adenovirus, total bacteria, astrovirus, rotavirus, norovirus, *E. coli*, pathogenic bacteria (nfs), total bacteria
Zhang Rensen 2012	Fujian	Fall	Outbreak/unclear	Gastroenteritis	Total coliforms, total bacteria

Note: nfs = not further specified.

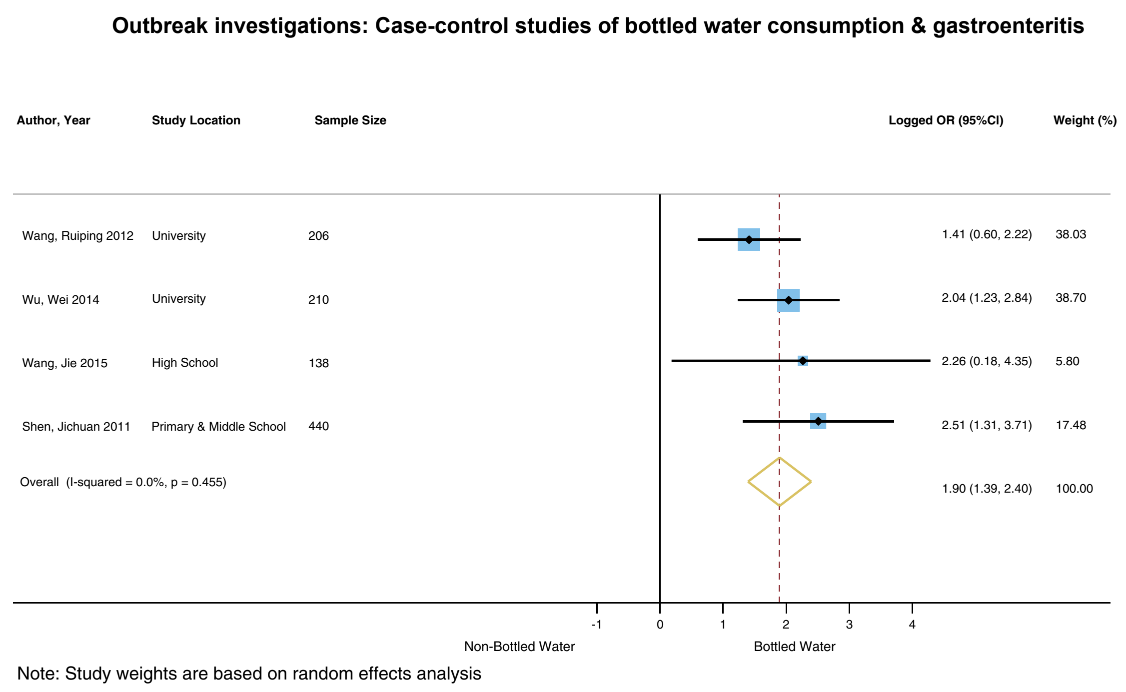

Figure 9. Forest plot—case-control studies of bottled water consumption and gastroenteritis.

(table S11 and figure S13). Looking at passing rate trends by publication year, for studies assessed to have a higher ROB (i.e. a higher likelihood of methodological shortcomings or other limitations) the average reported passing rates were lower overall (i.e. worse) compared with studies assessed to have a medium or low ROB for microbiological and chemical outcomes (figures S14 and S15).

One of the components used to estimate ROB was study sample size. As shown in table 8 (and table S12), we did not observe significant differences in mean passing rates for microbiological outcomes based on the number of bottled water samples used in the underlying studies. However, for studies reporting chemicals outcomes based on relatively large sample sizes (i.e. $\geqslant$61 bottled water samples)

Table 8. Meta-regression results for proportion of microbiological and chemical samples in compliance.

Variable	Passing rate (as a proportion) for microbiological outcomes			Passing rate (as a proportion) for chemical outcomes		
	Coef.	*SE*[a]	*p*-value	Coef.	*SE*[a]	*p*-value
Year of study publication	0.042	0.018	0.017	0.062	0.039	0.115
Study setting: rural (vs other)	−1.089	0.533	0.041	−2.214	0.711	0.002
Study setting: urban (vs other)	−0.173	0.171	0.311	0.201	0.375	0.592
Climate: warm/temperate (vs cold)	0.476	0.296	0.107	0.005	0.608	0.993
Climate: mild/subtropical (vs cold)	0.472	0.286	0.099	1.264	0.550	0.022
Climate: subtropical/tropical (vs cold)	0.742	0.341	0.030	1.054	1.049	0.315
Mid-level economic status (vs lower)	−0.098	0.258	0.704	−0.354	0.575	0.538
Higher-level economic status (vs lower)	0.319	0.259	0.219	−0.394	0.847	0.642
BW type/source: mineral (vs other)	0.271	0.161	0.092	−0.029	0.306	0.924
BW type/source: spring (vs other)	0.011	0.212	0.957	−0.376	0.610	0.538
BW type/source: purified (vs other)	0.349	0.152	0.021	0.880	0.358	0.014
Number of BW samples	−0.000	0.000	0.815	0.000	0.000	0.871
Model: number of observations		748			573	
Model: number of clusters (papers)		154			76	

Note: Excludes results from eight publications reporting results from outbreak investigations; BW = bottled water.
[a] Cluster-robust standard errors (to adjust for publications reporting results from multiple studies).

Table 9. Passing rates for microbiological and chemical outcomes by study climatic region.

	Median	Mean	SD	Studies
Microbiological outcomes				
Cold/mild temper	81.0	78.9	21.8	117
Warm temperate	81.2	78.8	20.4	201
Mild subtropical	90.6	85.3	16.4	334
Subtrop/tropical	99.0	90.2	15.1	143
Chemical outcomes				
Cold/mild temper	97.9	95.9	6.1	89
Warm temperate	100	96.6	10.4	140
Mild subtropical	100	97.5	5.3	209
Subtrop/tropical	98.9	96.1	8.9	155

Notes: Means and standard deviations adjusted using sample size based weights. Excludes results from eight publications reporting results from outbreak investigations.

Table 10. Passing rates for microbiological and chemical outcomes by bottled water size.

	Median	Mean	SD	Studies
Microbiological outcomes				
Small (<2 l)	62.1	72.1	20.8	89
Large (>10 l)	91.4	83.4	18.3	339
Small and large[a]	95.7	88.1	14.2	99
Only total coliforms				
Small (<2 l)	83.0	80.9	18.2	35
Large (>10 l)	95.2	94.3	7.3	106
Small and large	98.7	98.1	2.7	23
Chemical outcomes				
Small (<2 l)	100	96.9	11.9	111
Large (>10 l)	100	97.2	5.8	252
Small and large[a]	99.6	96.8	5.3	31

Notes: Means and standard deviations adjusted using sample size based weights. Excludes results from eight publications reporting results from outbreak investigations.
[a] Study authors reported combined results from analysis of small and large bottles.

the mean passing rate (91%) was significantly lower than for the smaller sample size categories (table S12; ANOVA with Scheffe's test, $p < 0.05$ for all three comparisons).

4.4. Author-provided hypotheses for observed contamination

The primary objectives of this review were to better understand the nature of bottled water quality in China and to elucidate some of the reasons for observed contamination, with the larger goal of potentially identifying management or policy approaches that could prevent or mitigate contamination. Based on the nature of the available reported data, we cannot responsibly make inferences with regard to reasons for the microbiological and chemical contamination observed. However, in most cases the authors of the individual papers did provide hypothesized explanations for their findings. To examine some common themes across studies, we extracted and synthesized author-provided explanations for observed contaminations (these author-provided explanations should be treated as informed opinions rather than as evidence).

Explanations for observed microbiological contaminants are summarized in figure 10 by climatic region. The hypothesized reasons varied, but in all climatic zones most authors postulated that contamination was due to insufficiently sanitary bottled water production, insufficient source water treatment, insufficient sanitation of reused bottles (typically the large ∼19 l bottles) and insufficient regulations or oversight. Slightly more authors of studies published in subtropical regions hypothesized that the source water was microbiologically contaminated, but this observation may be driven by other factors (e.g. more of China's less economically developed provinces are situated in subtropical regions).

Looking at author-provided explanations for observed chemical contamination over levels of annual consumption expenditures (figure 11), we see that most authors mention the same reasons as those offered for microbiological outcomes. However, more authors hypothesized that contaminated source water was an important factor, particularly in provinces with higher indicators of economic development. The confluence of industrialization, economic production, and higher province-level household consumption expenditures might partially explain this association, but as with the would-be explanations associated with microbiological outcomes, other factors are likely relevant as well.

4.5. Study limitations

Findings from our review summarize only publicly available data from eligible published studies and are unlikely to be representative of the situation across China with respect to bottled water quality for the approximately 20 year period from 1995 to the beginning of 2016. In addition, because the majority of the reviewed papers came from relatively more economically developed provinces (figure 2), our findings are likely not representative of less-developed provinces in China. Only a few studies reported which brands of bottled water were tested, or provided information specific to the source-water location; therefore, we were unable to analyze results based on where bottled water was sourced geographically, or where production facilities were located. We tentatively assumed that in most cases the bottled water sampled was from companies that sourced and produced the bottled water within the province where the study was conducted, or within the region surrounding the province. However, some studies may have focused their testing efforts on nationally available brands (e.g. Nongfu, Wahaha) that are sold across China and that are produced in multiple regional bottled water facilities.

As noted above, most of the eligible studies with extractable data in our review did not provide specific average concentrations and associated measures of variance (e.g. mean and SD) when reporting the results of analyses of microbiological and chemical parameters. Rather, most studies presented results only in terms of the passing rate, and we assumed that study authors were making these determinations (i.e. the proportion of samples in compliance) based on the relevant bottled water standards at the time of sample collection and/or study publication. Consequently, we were not able to assess the degree to which samples were not in compliance (i.e. for non-compliant samples we could not discern whether they fell just below, or markedly below, the standards). The lack of specific concentration data also limited our ability to compare results to specific standards, or conduct many of the subgroup analyses we pre-specified in our protocol. Likewise, for our meta-regression analyses, we were unable to include some variables hypothesized to be relevant because relatively few studies reported such data.

The limited number of eligible health outcome studies, and the nature of the data reported, prevented meaningful interpretation of results with regard to health impacts associated with bottled water consumption. Relatedly, we were unable to adequately quantify the extent of potential publication bias generally—i.e. we do not know how many studies with results on bottled water contamination may not have been published due to the nature and direction of their findings.

Finally, in our protocol we pre-specified that we would use the Grading of Recommendations Assessment, Development and Evaluation approach to assess and compare the degree of bias in eligible studies. However, because we found relatively few health-focused studies, and due in part to limitations based on the nature and extent of the available reported data, we chose to instead use an index-based approach for ROB.

More broadly, due to the extensive nature of this review it was beyond the scope of this paper to report

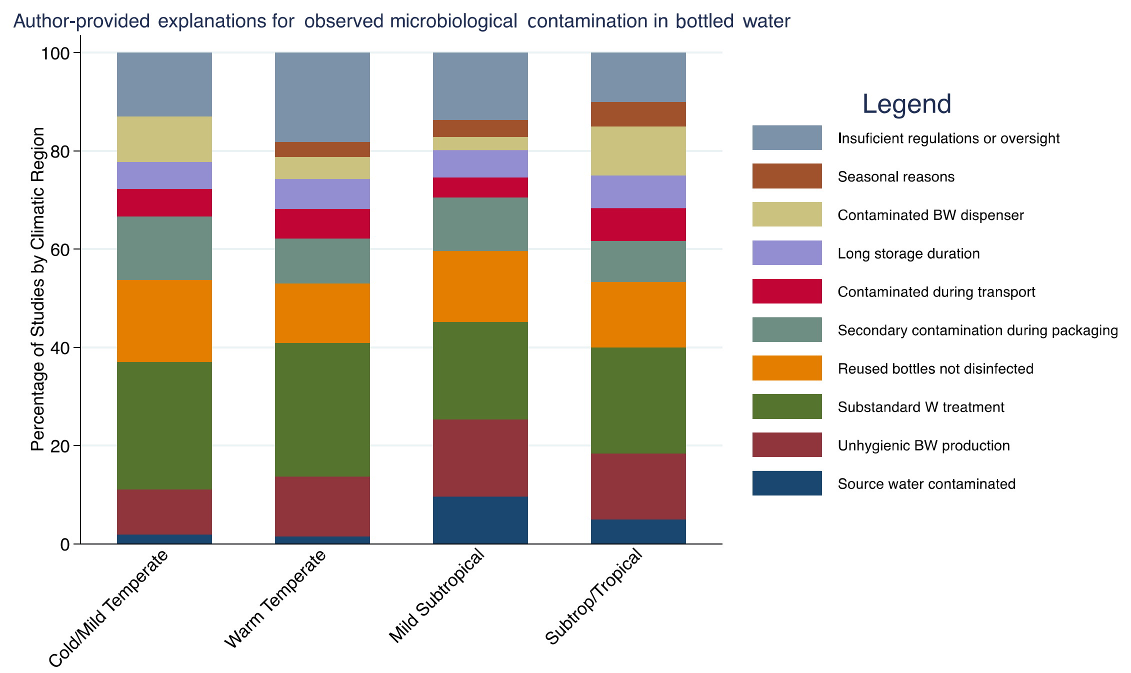

Figure 10. Hypothesized reasons study authors provided for observed microbiological contamination.

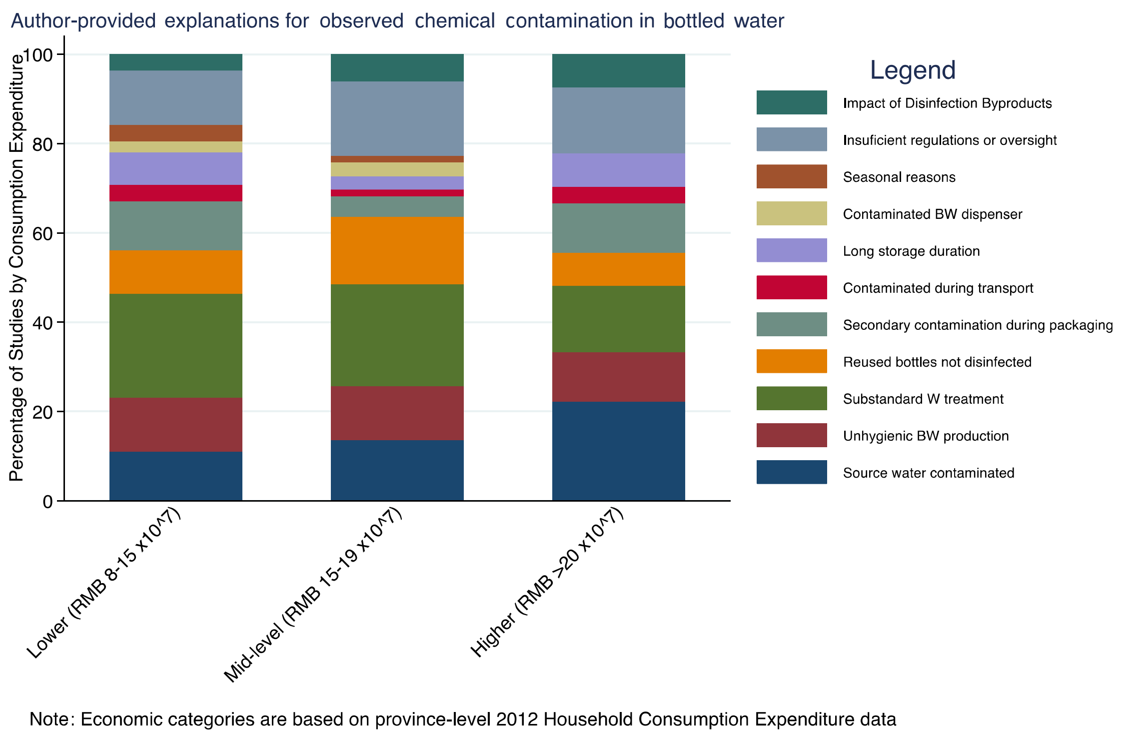

Figure 11. Hypothesized reasons study authors provided for observed chemical contamination.

summary findings for all the microbiological and chemical parameters for which we extracted data. We encourage interested readers to consult the SM excel data file should they wish to view or analyze results for less-commonly-reported parameters or otherwise explore the data we extracted for this study (available online at stacks.iop.org/ERL/17/013003/mmedia).

5. Conclusions

Included in the United Nation's 2030 Agenda for Sustainable Development is Sustainable Development Goal 6.1: '*By 2030, achieve universal and equitable access to safe and affordable drinking water for all*' [243]. Increasing consumption of bottled water and bottled water contamination are not issues unique to China, but China is unique in that, unlike most other countries, there exists a large body of published research on bottled water quality.

Overall, we observed that the vast majority of bottled water samples tested across the 625 reported studies from the 216 eligible publications for which we were able to extract data were in compliance with China's relevant bottled water standards. Over the period from 2005 to 2015, we also observed evidence of relatively stable or increasing (positive) overall trends in the proportions of samples reported to be in compliance with relevant bottled water standards. After controlling for other variables via meta-regression analysis, however, these associations were only statistically significant for microbiological outcomes overall, and not for chemical outcomes. We found only nine eligible studies that reported on health outcomes associated with bottled water consumption. Overall, due to the nature of the underlying available data and associated limitations, as well as geographic variation in the number of eligible studies, our findings should not be considered as representative of the general situation in China with respect to bottled water quality over this period.

Increasing reliance on bottled water in China and in other LMICs may serve to further exacerbate disparities in safe water access both directly—via the potential consumption of contaminated bottled water—and indirectly, via its normalization as a primary form of drinking water access. This normalization of bottled water for everyday drinking may in turn undercut efforts to expand and improve public water supply [5]. Of course, there are settings in China and in other LMICs in which centralized drinking water treatment and piped distribution are not feasible. In many such settings in China, government-run mini-utilities provide filling stations where people pay for and collect treated drinking water in large 19 l reusable bottles at costs much closer to those of piped drinking water than retail bottled water [244]. This type of kiosk-model for decentralized drinking water provision offers a relatively affordable and sustainable means of providing access to safe drinking water in regions with low population densities or challenging topography or hydrogeology. As noted in this review, one of the key challenges inherent in such an approach is ensuring sufficient disinfection of the reusable bottles between consumption and refill. In settings in China and other LMICs where centralized drinking water treatment and piped distribution is not feasible, efforts should be made to further expand well-regulated decentralized approaches for safe drinking water supply.

Across the world, bottled and packaged water is often accompanied by branding and marketing, promoting the notion that it is healthier and safer than alternative drinking water sources. In China, as well as in other LMICs and HICs, this trust may not always be warranted. The extent of, and impacts from, contaminated bottled water consumption remain poorly understood in both LMIC and HIC contexts—more research is needed on this issue. Given that bottled water will be part of the global waterscape for the foreseeable future, we hope that this work will stimulate more discussion and action on how to better regulate and improve bottled water production and quality. At the same time though, we hope this work will serve to further reinforce the need for LMICs—and HICs—to increase investments in the expansion and improvement of drinking water utilities as a far more equitable and sustainable pathway for providing reliable access to safe and affordable drinking water for all.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

A C designed the study, managed the data extraction, data cleaning, and quality assurance and control, conducted the statistical analyses, created the tables and figures, wrote the first draft of the manuscript, incorporated co-author feedback, and prepared the final manuscript and supplementary material files.

Q X, Q S, and X Y assisted with the search strategy design and piloting. J C, Q S, Q X, Y S, X Y, Y G, and J H conducted the search screening, full text identification, review, and data extraction. J C, Q S, and J H conducted extensive data cleaning, quality assurance, and control. J H created the map figures. J M C provided guidance on study design and contributed to results interpretation and the final manuscript. I R oversaw research assistant recruitment, provided guidance on study design, assisted with results interpretation, contributed to drafts, and helped write the final manuscript.

Conflict of interests

The authors declare they have no actual or potential competing financial interest.

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