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RESEARCH ARTICLE

Onsite sanitation systems and contamination of groundwater: A systematic review of the evidence for risk using the source-pathway-receptor model

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Abstract

The level of risk that onsite sanitation systems (OSS) pose to groundwater quality remains uncertain. The link between contamination and OSS can only be proved if the source, pathway, and receptor are investigated and confirmed when assessing contamination. The literature on the connection between OSS and groundwater contamination has been reviewed several times but with limited assessments of the extent to which the literature confirms that the source of contamination is an OSS, that a pathway has been identified, and that the receptor is groundwater. A systematic review was conducted on published studies and supports previous work that concluded that the removal and transport of contaminants from OSS to groundwater is complex and varies significantly according to local conditions. This variability means simple siting guidelines based on horizontal separation are not reliable. Though not always recognised in the literature, formation of a biological layer is important for removal of microbial pathogens. This layer takes months to form which impacts the performance of OSS that are new or subject to highly variable loading. Under ideal conditions of an unsaturated zone comprising fine material, faecal indicator bacteria can be reduced to detection limits within 10 metres distance. However, ideal conditions are very often not present. Multiple studies showed the presence of viruses in the absence of faecal indicator bacteria. Ingress of contaminated surface water into faulty boreholes/wells and contamination of wells from users are both often significant yet not adequately covered in the included literature. The review established that it is extremely difficult to eliminate the risk of groundwater contamination when OSS effluent is discharged into the subsurface. It is unsafe to assume that contamination can be prevented in areas with high OSS density, and further research is needed to determine the critical density threshold for different ground conditions.

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1. Introduction

Over the last twenty years onsite sanitation systems (OSS) have been growing faster than sewered sanitation in both rural and urban areas and globally, more people used on-site sanitation (46%) than sewer connections (42%) in 2022 [1]. At the same time, the use of groundwater for drinking water is on an upward trend. This is sometimes fuelled by increasing water scarcity due to climatic factors and the high levels of surface water contamination [2] and is exacerbated by the failure of urban water service operators to extend piped water to rapidly growing low income settlements. Half of the world's population relies on groundwater sources, and treatment prior to drinking may be limited. It is often therefore posited that public health maybe at increasing risk due to the rising combination of onsite sanitation systems and extraction of groundwater for drinking [3].

The term OSS has been used in literature to cover a very broad range of systems. In this paper, we mean systems that contain, store and/or very partially treat human excreta and wastewater on the same premises they are produced, and intentionally allow the liquid portion of the waste to leach into the ground also with the intention of treatment occurring. These are commonly in the form of pit latrines (including dry pits and wet pits such as pour flush or flush latrines) and lined tanks or septic tanks connected to an infiltrating system such as soak pits. Systems that allow the liquid fraction to be removed from the site through methods other than ground infiltration (such as a septic tank or sealed tank connected to a sewer or open drain) are also common but were not considered in this review.

The literature covering the connection between OSS and groundwater contamination has been reviewed several times. An early review was conducted in 1982 with the aim of understanding the state of knowledge around movement of microorganisms and nitrates through both unsaturated and saturated zones surrounding pit latrines [4]. The review covered literature on field investigations, laboratory studies, case histories of groundwater pollution and studies on the capacity of soils to remove bacteria and viruses. It aimed to use this information to assess the risks to groundwater from OSS in "developing countries" [4]. More recently, Graham and Polizzotto [5] conducted a systematic review of empirical studies of the impacts of pit latrines on groundwater quality. They found twenty-four studies that either directly assessed the transport of contaminants or used statistical methods to estimate the risk associated with the presence of pit latrines.

Both these reviews highlighted some common understanding of contaminant transport from an OSS to groundwater. They showed evidence that a biological layer (variously referred to as a 'biofilm', 'clogging layer', 'scum mat' or 'biomat') progressively develops around a pit latrine after the initial period of use and is crucial for removal of microbial contaminants, [4, 5]. Further reduction in pathogens occurred when effluent passed through an unsaturated zone. The presence of more than 2m of unsaturated fine soil and a hydraulic loading less than 50 mm/d was found to reduce microbial contaminants to minimal levels [4]. Saturated conditions or fissured bedrocks over a shallow soil layer resulted in greater horizontal travel distances of up to 25m for bacteria, 50m for viruses and 26m for chemicals [5]. Some bacterial and viral species adsorbed to various ground media may be desorbed during heavy rainfall which can rapidly increase concentrations and risk of groundwater contamination [4].

Both reviews highlighted nitrate as the chemical contaminant of most concern. Organic nitrogen in waste converts to ammonia as it breaks down in a pit or septic tank. The unsaturated zone was typically aerobic, and hence this ammonia was rapidly oxidised to nitrate. No evidence was found in the reviews to indicate appreciable accumulation of ammonia in groundwater, though this is theoretically possible if sub-surface conditions remain anaerobic [5]. Nitrate may be removed through denitrification in either the unsaturated zone or the aquifer given a low or zero oxygen environment and the presence of an electron donor, which though often organic carbon, could be inorganic compounds such as reduced iron or sulphur [4, 6]. Nitrate concentrations may also be reduced by dilution in the aquifer, with the amount of reduction depending on the recharge rate of the aquifer compared to the load from OSS. However, denitrification does not always occur, and dilution may be limited. Concentrations of nitrate in groundwater above drinking water standards have been regularly found and attributed to OSS [5].

The reviews also concluded that it is exceedingly difficult to rely on simple siting guidelines such as a horizontal distance between an OSS and a well or bore due to the high variability in contaminant removal in different ground conditions and the limited understanding of the mechanisms and conditions that affect contaminant removal. They concluded there is a need to empirically test current siting guidelines [4, 5].

Another review conducted by Pang [7] summarised the available literature on microbial removal rates in different ground conditions and compiled 87 datasets covering both bacteria and virus removal. Removal rates were calculated and expressed as $\log_{10}$ organisms removed per metre to provide a dataset that could be used to estimate safe setback distances from an OSS. The data was split into removal rates for soils (defined as the first 1m of ground comprising the biologically active layer), vadose zone (defined as the unsaturated zone from the end of the soil to the groundwater table) and aquifers. The data show microbial removal rates in the biologically active soils between 0.1 to 10 $\log_{10}$ removal per metre, 0.1 to 1 $\log_{10}$ per metre in the vadose zone and aquifer removal rates varying from 10^{-4} per metre for karst limestone to 1 $\log_{10}$ per metre for sand aquifers [7]. Such high variability of removal rates with different sub-surface conditions explains how in one set of sub-surface conditions investigators can find faecal indicator bacteria (FIB) are reduced to minimal levels with 2m of unsaturated zone [4], while in different sub-surface conditions, groundwater contamination is measured up to 50m from pit latrines [5].

These three previous reviews considered the different categories of pathogens: protozoa, helminths, bacteria, and viruses but came to differing conclusions about their removal rates. Lewis, Foster [4] assumed the large size of helminths and protozoa would ensure they are effectively strained out in a short distance and found only sparse information on viruses, so primarily focussed on FIB. Graham and Polizzotto [5] found no studies assessing protozoa or helminths and only one study on viruses that met their systematic review criteria. They concluded that there is a greater travel distance for viruses than FIB [5]. However, Pang [7], who used a much broader data set, concluded that virus removal rates were of the same order of magnitude as bacteria, and did not report any data on helminths and limited data on protozoa.

In 2014, a general review of groundwater contamination covering all potential sources was conducted in USA and Canada. Forty-five studies were identified where the presence of pathogens in groundwater was attributed to septic tanks. However, the review did not explore the validity of the attribution reported [8].

Most recently in 2023, Gwenzi, Marumure [9] conducted a narrative review on evidence for contamination from pit latrines, highlighting the presence of emerging contaminants in pit latrines as well as pathogens and nitrates. They argued there is a need for regular "quantitative systematic reviews combining bibliometric and meta-analytic methodologies".

Most of studies included in previous reviews fail to rule out indirect/localised pathways of contamination seen in the aquifer. This is important as contamination could have multiple other pathways such as animal or human waste entering through defects in well or bore construction, or contamination of hand pumps and tube wells at the point of collection. It has been argued that these are the more significant source of contamination, at least in some circumstances [10]. This study therefore sets out to update previous reviews but expand on them

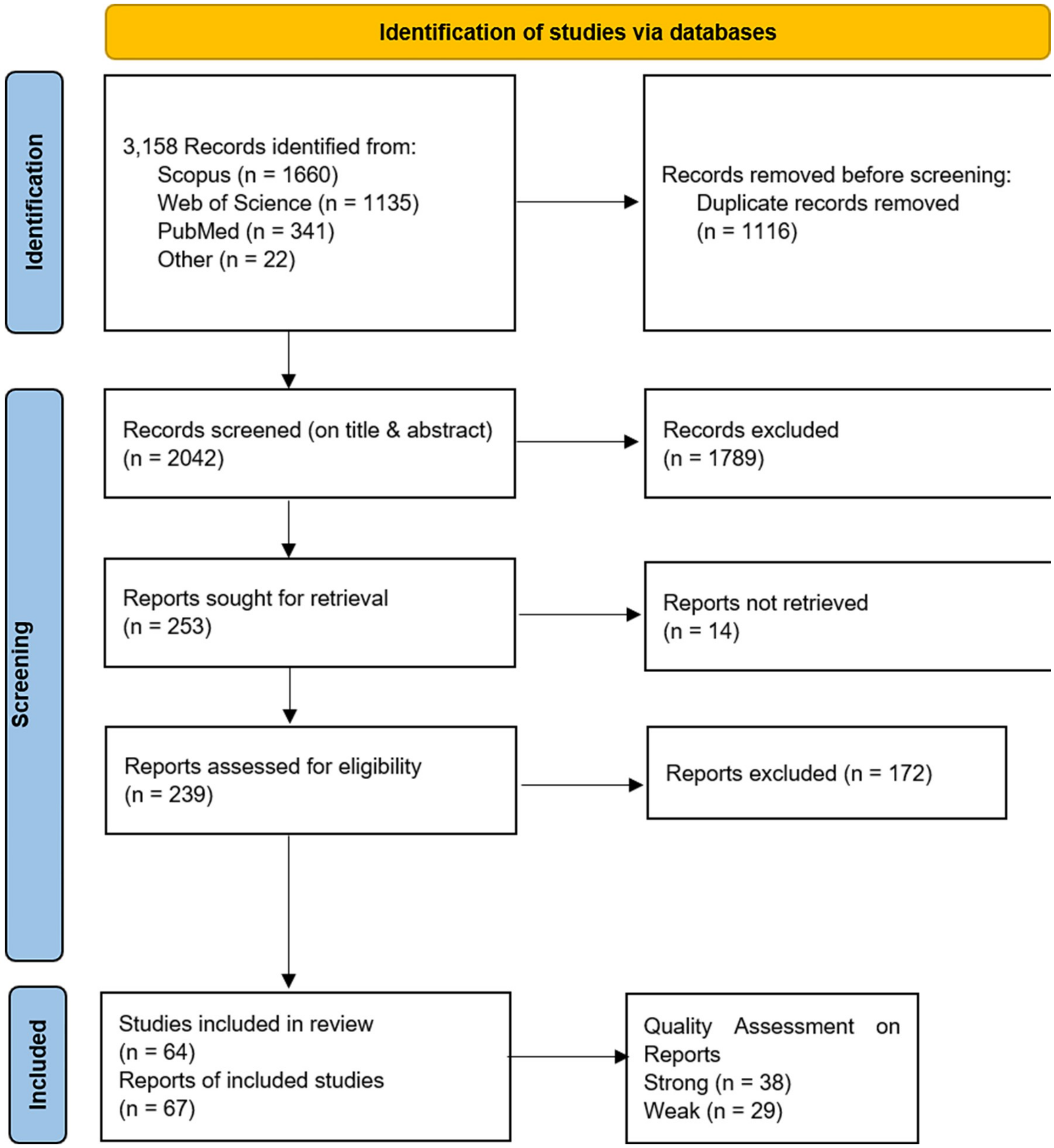

Fig 1. Prisma diagram.

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by using the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol [11] as shown in Fig 1. We adopted a "source-pathway-receptor" (SPR) approach [12], so providing the meta-analytic methodology argued for by Gwenzi, Marumure [9]. The SPR is used both to structure the literature search and to assess the quality of evidence in the literature. It requires that a study clearly identifies OSS as a source; shows a viable pathway for contaminants to be transported to the receptor; and has evidence of contamination at the receptor.

The review is also broader in scope than previous reviews by including all OSS discharging effluent into the ground such as septic tank systems, soak pits, cess pools and pit latrines.

Mechanisms for contaminant transport and removal from OSS to groundwater are likely to be the same regardless of the type of OSS and including these may bring in evidence from studies not picked up by others, who focused on pit latrines only.

Finally, improvements in technology since 2013 have enabled more studies to look at viruses and use microbial source trackers, potentially addressing one of the findings of Graham and Polizzotto [5], that the quality of experimental techniques and chosen indicators was highly variable. Hence, increasing use of these novel techniques may have since generated new evidence on the transport of contaminants from OSS to groundwater.

2. Methodology

2.1 Source Pathway Receptor (SPR) model

Using the SPR model, the source is the point of origin of the contaminant; in this case, the OSS. A wide range of terms are used to describe the various OSS and the terminology is often inconsistent. For the purposes of this study, we have grouped OSS into:

Separated function OSS (Store/treat structures separated from infiltrate structures): These are systems composed of a watertight container that receives excreta, flushing water and/or occasionally greywater, allows for some level of primary treatment before discharging the supernatant into a separate structure where infiltration into the subsurface occurs. Typically, these systems are referred to as septic tanks with soak pits or leach fields.

Combined function OSS (store/treat/infiltrate in same structure): These are systems composed of a lined/unlined pit that receives human excreta, flushing water, cleansing materials and/or grey water and allows direct infiltration into the subsurface. This covers systems such as pit latrines, VIP latrines, pour flush latrines, aqua privy. In some papers these systems that receive flushing water are also referred to as septic tanks.

Our reason for using these two categories is that there might be a difference in how they interact with groundwater on the basis that separated function systems should in theory provide some greater level of treatment prior to effluent being infiltrated and would usually handle a higher volume of water as they include flushing water and/or grey water [13].

The pathway is the route through which the pollutant travels. Pathways are broadly categorized into two as follows [12] and as shown in Fig 2:

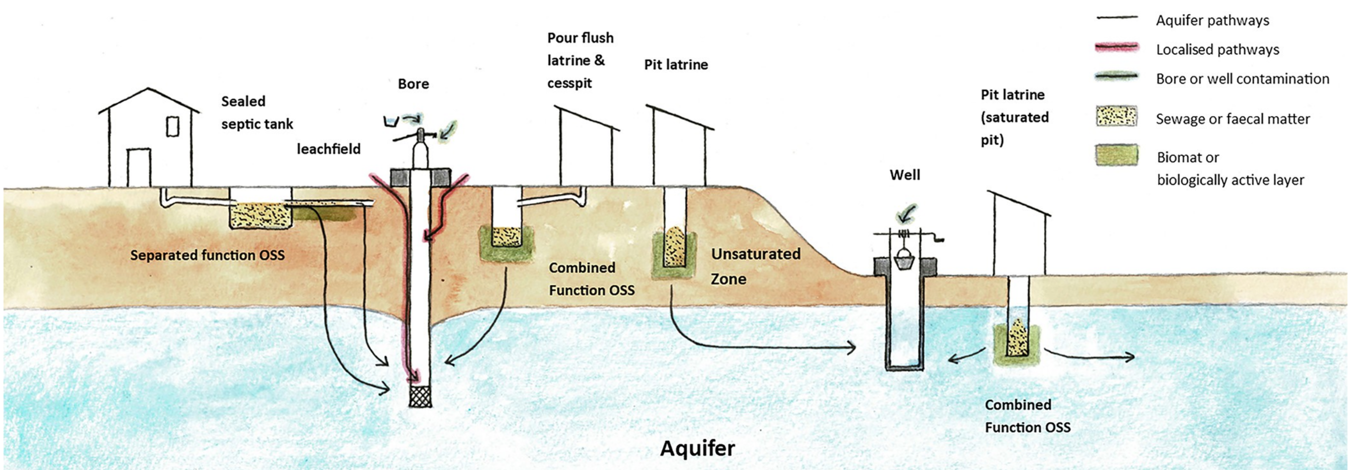

Fig 2. Conceptual diagram of OSS, pathways and receptors.

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- Aquifer pathway–Direct movement of contaminants from the OSS into the groundwater through the pores in the soil/rock structure
- Localised pathway–Indirect movement of contaminants from the OSS into groundwater as a result of failures in the design and/or construction of the groundwater supply system (e.g., well, borehole, spring etc.).

The receptor is the groundwater located within a borehole or a well.

2.2 Literature search strategy

The search terms were grouped according to the source-pathway-receptor model as shown in Table 1. Words used interchangeably to mean "latrine," "septic tank" and "soak pit" were used to describe the source of the contaminants. The pathway and receptor were described using variations of the terms, "groundwater", "borehole" and "well". Words that were associated with non-human contamination sources such as animals, mines and fertilizers were used to exclude articles.

Searches were made using Scopus, PubMed, and Web of Science databases covering the period 1900 to August 2023. The search was done in two phases, one covering 1900 to June 2020 by the lead author followed by an update covering 2020 to August 2023. Key word strings are presented in Table 2.

2.3 Eligibility and review

2.3.1 Title & abstract screen. Articles were screened on title and abstract by two reviewers using Rayyan software [14] and based on the criteria presented in Table 3.

2.3.2 Full text screen. The screening was done against the criteria in Table 4. Criteria 'C4', 'C5', and 'C6' represent the application of the source-pathway-receptor model to screen out papers that did not track contaminants from an OSS via a pathway into the receptor.

Table 1. Search terms using the SPR model.

Source—Onsite containment in the ground	
1	"Pit latrine*" OR pit-latrine* OR latrine* OR toilet* OR "septic tank*" OR "soak* tank*" OR "soak* pit" OR "leach pit*" OR "cess pit" OR cesspit OR "cess pool" OR cesspool
2	(onsite OR on-site OR "onsite") W/3 sanitation
3	Fecal OR faecal OR Feces OR Faeces OR excret*
Pathway/Receptor—Passage mechanism for pathogens	
4	Groundwater OR "ground water" OR "groundwater" OR aquifer
5	"Shallow well*" OR "shallow borehole*" OR borehole* OR hydro-geologic* OR "hydro geologic*" OR underground OR hydrogeochemical
6	Well OR Wells W/5 Water
7	Contamin* OR pollut*
Exclusion terms–non-human source	
8	animal OR bird OR manure OR irrigat* OR "surface water" OR river OR marine OR landfill OR "land fill" OR "solid waste" OR oil OR gas OR mining OR agriculture
	Combined Searches
9	(1 OR 2 OR 3) AND (4 OR 5 OR 6) AND 7 AND NOT 8

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Table 2. Search key word strings.

Database	Search string
Scopus	(TITLE-ABS-KEY ("Pit latrine*" OR pit-latrine* OR latrine* OR toilet* OR "septic tank*" OR "soak* tank*" OR "soak* pit" OR "leach pit*" OR "cess pit" OR cesspit OR "cess pool" OR cesspool OR fecal OR faecal OR feces OR faeces OR excret*) OR TITLE-ABS-KEY ((onsite OR on-site OR "onsite") W/3 sanitation) AND TITLE-ABS-KEY (groundwater OR "ground water" OR "ground-water" OR aquifer OR "shallow well*" OR "shallow borehole*" OR borehole* OR hydro-geologic* OR "hydro geologic*" OR underground OR hydrogeochemical OR ((well OR wells) W/5 water)) AND TITLE-ABS-KEY (contamin* OR pollut*) AND NOT TITLE-ABS-KEY (animal OR bird OR manure OR irrigat* OR "surface water" OR river OR marine OR landfill OR "land fill" OR "solid waste" OR oil OR gas OR mining OR arsenic OR agriculture))
Web of Science	("Pit latrine*" OR pit-latrine* OR latrine* OR toilet* OR "septic tank*" OR "soak* tank*" OR "soak* pit" OR "leach pit*" OR "cess pit" OR cesspit OR "cess pool" OR cesspool OR Fecal OR faecal OR Feces OR Faeces OR excret* OR (onsite OR on-site OR "onsite") NEAR/3 sanitation) AND TS = (Groundwater OR "ground water" OR "ground-water" OR aquifer OR "shallow well*" OR "shallow borehole*" OR borehole* OR hydro-geologic* OR "hydro geologic*" OR underground OR hydrogeochemical OR ((Well OR Wells) NEAR/5 Water)) AND TS = (contamin* OR pollut*) NOT TS = (animal OR bird OR manure OR irrigat* OR "surface water" OR river OR marine OR landfill OR "land fill" OR "solid waste" OR oil OR gas OR mining OR agriculture)
PubMed	((((“Pit latrine*” OR pit-latrine* OR latrine* OR toilet* OR “septic tank*” OR “soak* tank*” OR “soak* pit” OR “leach pit*” OR “cess pit” OR cesspit OR “cess pool” OR cesspool OR Fecal OR faecal OR Feces OR Faeces OR excret* OR ((onsite OR on-site OR “onsite”) N/3 sanitation))) AND (Groundwater OR “ground water” OR “ground-water” OR aquifer OR “shallow well*” OR “shallow borehole*” OR borehole* OR hydro-geologic* OR "hydro geologic*" OR underground OR hydrogeochemical OR ((Well OR Wells) N/5 Water))) AND (contamin* OR pollut*)) NOT (animal OR bird OR manure OR irrigat* OR "surface water" OR river OR marine OR landfill OR "land fill" OR "solid waste" OR oil OR gas OR mining OR agriculture)

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2.4 Quality assessment

Papers that passed through the full text screening were then given a quality rating by assessing against the criteria illustrated in Fig 3 and explained in Tables 5 and 6. Studies were rated “weak methodology” if they answered “No” to any of the questions (1–4) and “strong methodology” if they answered “Yes” in all questions presented in the flow diagram in Fig 3. The purpose of this quality assessment is to provide a set of papers we consider to have strong evidence that we can rely on as the primary source for drawing conclusions. The process worked as a series of decision points, with a paper categorised as weak once it failed one decision point, hence we did not assess all papers against all quality criteria. A full list of papers, strong and weak, is provided in the S1 Checklist.

Table 3. Title and abstract screening criteria.

Item	Inclusion Criteria	Exclusion Criteria
Article type	Published–lab, field, and observational papers	Unpublished documents and modelling papers that had no real-world data
Language	English	Non-English
Source	Human faeces and urine contained underground in a structure termed as or similar to a “pit latrine, septic tank or soakaway”	Animal faecal or urine containment Human excreta in off-site systems e.g., sewage Note: Mixed sources with both animal and human excreta were included at this stage.
Pathway	Aquifer and localized pathways by confirmation or indication	Pathway not linked to OSS Note: This assessment was often minimal as insufficient information on pathways was presented in the abstract
Receptor	Groundwater	Surface water, coastal/marine, recreational water bodies with no groundwater data
Contaminants	Microbial and nitrogen	No contaminants tested, or exclusively tested pharmaceutical products, and contaminants of emerging concern e.g., nicotine, caffeine surfactants & industrial additives.

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Table 4. Full text screening criteria.

Criteria	Explanation / Reason to exclude papers
C1. Does the scope of the paper extend beyond testing of OSS modifications?	Field or laboratory trials of the performance of different OSS. While these provide useful information on performance, they were not aimed at showing an OSS-groundwater contamination link.
C2. Is the full text paper accessible?	Full text could not be obtained.
C3. Is specific data on microorganisms (pathogens) and/or nitrogen included?	Abstract & title review may not have been clear that the paper did not have data and so this was screened again at full text review.
C4. Is the contaminant tracked through a pathway?	Did not provide any information on ground conditions / aquifer or other information to show it is possible for contaminants to move from OSS to receptor. For example, paper looked at data from wells and tried to correlate with OSS (location, density). Although a statistical correlation may be shown, paper did not provide a plausible pathway or any other evidence to show causation.
C5. Is the contaminant tracked at the receptor?	No data on groundwater at a point of extraction. For example, may have sampled soils around an OSS but not sampled groundwater/aquifer.
C6. Were other sources of the contaminant excluded?	Conducted in locations with multiple potential sources (e.g., livestock, open defecation) and did not have any means to exclude other sources or quantify OSS contribution compared to other sources. Did not clearly establish the presence of OSS systems (e.g., might have been assessing well water quality and mentioned OSS as likely source without any data confirming they are present.)

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For criteria 4, there is a wide range of techniques that studies have used to exclude other potential sources of groundwater contamination. These techniques were analysed and rated as presented in Table 6.

3. Results and discussion

3.1 Results

A total of 3,158 results were identified from the search in Scopus (1,660), Web of Science (1,135) and PubMed (341). A further 22 articles were added through citation searches. 2,042 articles remained on removal of duplicates. 253 papers remained after assessment of the titles and abstract. Further review by content screening resulted in 67 papers that met the eligibility criteria. There were three studies where two separate papers were published covering different aspects of the same study. The results of the PRISMA screening criteria are shown in Fig 1.

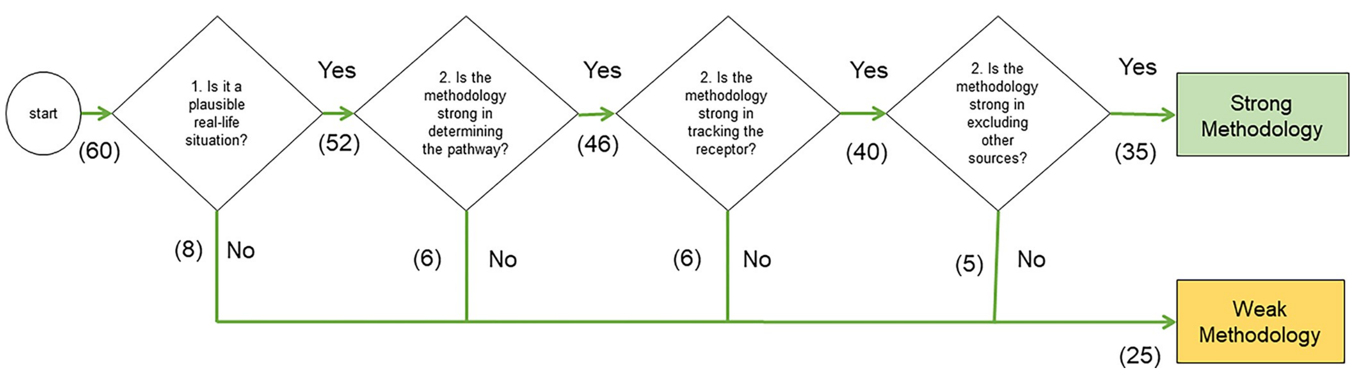

Fig 3. Quality assessment results.

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Table 5. Quality assessment criteria.

Question	Examples in studies answering "Yes"	Examples in studies answering "No"
1) Is it a plausible real-life situation?	• Field studies of existing OSS in use • Constructed test sites that used realistic household excreta loads and patterns	• A laboratory experiment in columns. • Constructed test sites with artificial wastewater and/or dosing regimens.
2) Is the methodology strong in determining the pathway?	• Used a tracer for pathway–dyes, SF6, Li, etc. The tracer may have been injected as part of a test or may have been a substance unique to OSS and tracked to receptor. • Had multiple sampling points that tracked contaminants along the pathway from source to receptor. • Developed a groundwater flow model to track contaminant pathways and the model was calibrated with real world measurements. • Contained information on the nature of the soils, ground conditions, groundwater levels, movement and direction	• Statistical correlation of density of OSS with concentration of contaminants without information on the nature of the soils, ground conditions, groundwater levels, movement and direction.
3) Is the methodology strong in tracking the receptor?	• Purpose-built sampling wells or piezometers and which described methods used to prevent cross contamination. • Groundwater sources if study used some means to ensure samples represented groundwater quality and were not cross contaminated in sampling.	• Looked at fecal indicator bacteria and used samples from groundwater sources but did not provide a method to ensure that the samples were representative of groundwater quality and not affected by contamination from sources such as birds, prior use of contaminated buckets, ropes, etc.
4) Is the methodology strong in excluding other sources?	Refer Table 6	Refer Table 6

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Table 6. Methods used for excluding other sources of contamination.

Method for excluding other sources or demonstrating contamination is human source.	Method Rating	Explanation	Examples of studies that used this method
Statistical correlation between distance to OSS or density of OSS's and well FIB and NO_3	Weak	Statistical correlation alone leaves open many other possible sources of contamination and does not show a pathway. Studies that solely relied on this method were considered weak.	[15, 16]
Network of bores or sampling points surrounding the OSS being studied.	Strong	Provided it is clear other sources are excluded within the network & that upstream groundwater is not contaminated.	[17–20]
Cl:Br ratio	Weak	Basis is that anthropogenic sources have more NaCl and so higher Cl:Br ratio but doesn't easily differentiate between human/animal and whether human is OSS or other source.	[21, 22]
Stable isotopes - ^{15}N and ^{18}O in NO_3	Weak	Based on some data that sources of nitrate (e.g., chemical fertilizer, sewage) have different ratios of these isotopes. However method has challenges when multiple sources are present [23].	[24, 25]
Microbial Source Trackers	Strong-	A range of substances are used that are intended to solve the problem of E Coli, F Coli or NO3 not being unique to human sources. • HF183 (qPCR test for the 16S rRNA gene of human associated bacteroid) • qPCR used to match virus samples of source and receptor.	[26, 27]
Pepper Mild Mottle Virus	Weak	Pepper mild mottle virus is a virus of plants such as pepper which has been detected in human excreta in many countries. It is proposed as a viral indicator in much the same way as E Coli is a bacterial indicator of possible human contamination. However, its presence is not unique to human excreta, so detection doesn't exclude other sources.	[28]
Other chemicals likely to be human specific	Strong if the chemical is human specific.	Some of the chemicals used were: • Pharmaceutical products • Aspartame • Caffeine • Acesulfame & Sucrose (artificial sweeteners)	[29, 30]
DNA analysis to characterize bacterial community	Weak	The argument is that if waste from an OSS is the source, the community of bacteria in impacted wells will be different to wells without OSS influence.	[31]

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3.2 Classification of included papers

57% (38 Nos.) of the 67 included studies were rated "strong methodology" while the remaining 43% (29 Nos.) were rated as having a "weak methodology" on analysis using the quality assessment flow diagram (Fig 3).

Eight studies were rated weak because they did not pass the plausible real-world situation test, typically they involved experimental setups with artificial dosing regimens. Seven papers were rated weak because they provided limited information on the pathways that contaminants moved along. Six papers were rated weak in tracking the receptor, commonly because they used data from wells or bores where other potential contamination sources such as animals and dirty collection buckets/ropes could not be ruled out. Of the studies that made it through to the fourth test, a further eight were assessed as having a weak method of excluding other sources.

Strong studies included in our review are summarised in Table 7.

Papers were grouped by the income status of the country as of 2022 using World Bank definitions (Table 8). Most of the included studies were undertaken in HICs. Studies from HIC or UMIC were more likely to be rated "strong methodology" presumably because more resources are available in these countries to use more advanced techniques to investigate the sources, pathways and receptors.

Table 8 also shows the split of technology types in the included papers according to the income status of the country where the study was located. Many papers provided only a minimal description of the type of technology used and so for 12 of the included papers we were not able to be confident which of the two broad categories we developed was being used in the study. Separated function structures are the most used OSS technology in HICs and therefore formed most of the studies (33Nos.) in the category. Most combined function structures studies (9Nos.) were in LMICs.

The included papers are presented by year of publication in Fig 4. The number of papers that were considered suitable for inclusion has increased in the last ten years with a maximum of 19 papers included between 2017–2023. This may reflect both increased interest in this topic and/or improved approaches resulting in less papers being excluded in more recent years.

Table 9 shows aspects of the included studies. Studies were either cross-sectional which meant that they looked at a situation at a particular point in time or longitudinal meaning that they looked at the variability over time, often with the aim of looking for seasonal impacts. Any study that covered at least a whole year of data was classified as longitudinal and nearly half of studies did this as shown in Table 9. A total of nine papers also looked at the impact of rainfall events, usually by recording daily rainfall and measuring contaminants with sufficient frequency to allow some conclusions to be drawn about the impact of rainfall events.

Most papers [54] only looked at the aquifer pathway and of the few [14] that considered localised pathways, most [9] had a weak methodology. Faecal indicator bacteria were most widely used [47] studied, followed by nitrogen [37]. Viruses were the least investigated [13] although they are receiving increasing attention as analytical methods improve.

3.3 Discussion

Of the studies we reviewed, those with strong methodologies provide new insights into the interaction between OSS and groundwater. Environmental, physical, and social characteristics may vary between and within developing and developed countries. Although two-thirds of the strong studies were conducted in the developed countries, this section summarizes the

Table 7. Summary of strong studies.

Authors	Country	OSS Type	Contaminants	Subsurface Conditions	Distance to groundwater	Findings
Caldwell & Parr, 1937 [18]	United States	P	FIB, N	Unconsolidated fine gravel to clayey soils with impervious stratum underlaying the latrine bore and flow	Latrine extended to groundwater	After 3 months biofilm formed, and FIB retreated so that by 7 months FIB was only detected practically at the latrine wall.
Caldwell, 1938 [17]	United States	P	FIB	Fine gravel to clayey unconsolidated soils over rock formation	0.6m	3 log FIB removal at 0.3m. No FIB detected at horizontal distance of 1.2m from latrine.
Dyer, 1941 [32]	India	P	FIB	Alakaine soils with between 12% and 23% clay content	Latrine extended to groundwater	Pollution initially extended beyond 5 foot, then retreated to between 2.5 to 5 foot horizontally.
Reneau, 1977 [19]	United States	S	N	Sandy loam	water table mounds around drainpipes	Tracked Nitrogen transformations and showed nitrification and denitrification
Viraraghavan, 1978 [33]	Canada	S	FIB	Sandy clay & Clay	0 to 0.15m	3 log FIB removal after 15m horizontal travel
Starr and Sawhney, 1979 [34]	United States	S	N	Coarse Sandy well drained soils	0.9m max depth measured, groundwater probably lower	Complete nitrification in a dry year, but no nitrification in a wet year when subsurface seems to have been saturated
Lewis et al., 1980 [20]	Botswana	P	FIB, N	Saturated and unsaturated clayey soils to weathered granite	3m	High nitrate > 500 mg/L in some locations. E Coli detected 5m horizontal. Observed cracks in clay
Stewart and Reneau, 1981 [35]	United States	S	FIB	Poorly drained fine to coarse loamy soils	Level of water table varied with seasons	In dry season FIB not detected at 10m horizontal, 5 orgs/100mL at 5m. In wet season FIB >10,000 orgs/100mL
Vaughn et al., 1983 [36]	United States	S	Virus, FIB, N	Sandy soils—shallow aquifer distance between static GW level and bottom of leaching pool was 0.6m	3.6m	Detected virus in a well 18m deep, 67m horizontal from septic, but FIB rarely detected beyond 1.5m
Reddy and Dunn, 1984 [37]	United States	S	N	Fine sandy loams	Not stated	Nitrate reduced with depth
Chen, 1987 [38]	United States	S	FIB, N	Sandy loams, Silty Loams, Loamy sands and gravelly silty loams	n/a	The depth to the ground water from ground surface and the distance of the ground water from the discharge point of the sewage system are main factors influencing pattern and severity of ground water contamination
Al Hajjar et al, 1988 [39]	United States	S	FIB, Virus	Sands, loamy sands and sandy loams	About 2m	Limited (1 log) reduction in virus at 6m horizontal, FIB largely below detection by 0.3m horizontal
Cogger et al, 1988 [40]	United States	S	FIB, N, virus	Sandy soils	0.3–0.6m	0.6m unsaturated zone provides effective FIB removal (4 log) and 3 log virus removal. Saturated conditions resulted in significantly worse performance
Postma et al., 1992 [41]	United States	S	FIB, N	Coarse grained beach soils-well sorted medium sands	1.6–1.7m	4 log FIB reduction at 2m horizontal, 5 to 6 log removal by 6m horizontal. Seasonally used septic tank, found biological layer to be absent
Gondwe et al., 1997 [42]	Tanzania	U	FIB, N	Silty sands underlain by hard clay and clayey sand layers	Pits below groundwater level	10^5 to 10^6 F coli in all shallow bores
DeBorde et al., 1998 [43]	United States	S	Virus	Sand and gravel medium sand in vadose zone- Unconfined sand & gravel aquifer	2.8m from leach pipe to groundwater	Dosed coliphages reduced 6 Logs to below detection level by 38m horizontal
Smith et al., 1999 [44]	Indonesia	U	FIB, N	Porous volcanic soils	0.38m	Nitrate over drinking water standard attributed to OSS

(*Continued*)

Table 7. (Continued)

Authors	Country	OSS Type	Contaminants	Subsurface Conditions	Distance to groundwater	Findings
Chen et al., 2001 [45]	Taiwan	U	FIB	Not indicated	Not specified	Disease outbreak attributed to OSS 10m horizontal from well. Submersible pump whose outlet pierced the lining of the well near the ground allowing entry route for contaminants.
Geary, 2004 [46]	Australia	S	N	Sandy soils	0.4–0.8m	Ammonia converted rapidly to nitrate, nitrate lost through denitrification and plan uptake
Geary, 2005 [47]	Australia	S	N	Sandy soils	0.4–0.8m	As above
Alexander et al., 2008 [48]	United States	S	FIB, Virus	fine sandy loam over fractured bedrock (Karst)	Not stated	New septic system identified as cause of waterborne illness in restaurant. A leak prior to leach pits possible cause, but leach pit also shown to be hydraulically connected to water supply.
Harden et al., 2008 [49]	United States	S	FIB, N	Sandy soils, underlying karst aquifer	1.3–4.5m	0.4–4 m thick sandy surficial soils and underlying karst aquifer allow rapid contaminant transport and limit the ability to attenuate NO_3
Katz et al., 2010 [24]	United States	S	FIB, virus, N	Thin sands and clays overlying a karst aquifer	2.6–4.4m	Indicator bacteria and human enteric viruses were only intermittently in groundwater. Contaminant movement to groundwater beneath each septic tank system also was related to water use and differences in lithology at each site.
Banerjee, 2010 [50]	India	P	FIB	Clayey silty soils & Sandy gravel soils	varied—0.5–5m, some pits saturated	Maximum horizontal travel of FIB was 6m, a clay barrier effectively stopped FIB transport
Sonbul et al., 2011 [51]	Saudi Arabia	S	FIB, N	Coarse sand to gravel soils with traces of silt and clay	7–12m	FIB not detected in receptor wells, but nitrate up to 193 mg/L
Borchardt et al, 2011 [52]	USA	S	FIB, virus	sandy loam topsoil, sandy clay to 0.76m. Glacial till with large cobbles to at least 3m depth then fractured dolomite, often with dissolution having enlarged fracture opening and pores	35m	Virus attributed to septic source detected at well 85m deep and 188m horizontal distance from septic
Keegan et al, 2014 [53]	Ireland	S	FIB, N	6 sites covering low permeability clay/ bedrock to high permeability sandstone till	not specified	Performance varies greatly with permeability and composition of subsoil, with high permeability sites presenting a risk to groundwater
Islam et al., 2016 [54]	Bangladesh	U	FIB	Sandy Loams, Loam, Loamy sands, Clayey Loams	7–20m	the safe distance from the tube well to the pit latrine varied from site to site depending on the horizontal and vertical distances of the tube well as well as hydrogeological conditions of a particular area.
Van Ryneveld et al., 2016 [55]	South Africa	P	FIB	1m silty sand, dense gravel and stiff sandy clay soil (residual granite)	15m	At horizontal distances of 3 m from the soak away, levels of the FIB and nitrogen had dropped to values consistent with the background levels
Ravenscroft et al., 2017 [10]	Bangladesh	P	FIB	2 sites—on sandy, more permeable sediments, deep water tables and 2 sites—on river, fine sediment, internal sedimentary structures & shallow water tables—All sites have 3-5m thick aquitards where latrines were constructed/Jaijira-silt & clay	Up to 30m	leakage from pit latrines is a minor contributor to faecal contamination of drinking water in alluvial-deltaic terrains

(*Continued*)

Table 7. (Continued)

Authors	Country	OSS Type	Contaminants	Subsurface Conditions	Distance to groundwater	Findings
Higgins et al., 2020 [31]	USA	S	FIB, N	glacial fluvial sand & gravel	4.5m	Highly likely that domestic wells have elevated nitrate arising from local septic leach fields, not farm fertiliser. FIB not detected in wells.
Murphy et al, 2020 [26]	United States	S	FIB, virus	Not indicated	Unclear	Evidence of human faecal contamination in the private wells located 9 to 54m horizontal from household septic systems. Evidence that rainfall events play a key role in transport.
Rakhimbekova, et al., 2020 [30]	Canada	S	N	fine sand	not stated	Tracks nitrogen plume through groundwater and shows nitrogen removal at groundwater-lake interface
Mattioli et al, 2021 [27]	USA	S	FIB, virus	Fine sand, silt, clay on surface overlying sandstone \ siltstone \ shale bedrock, slopes towards well	unknown	An overloaded septic system was the likely source of human faecal and norovirus contamination in a well
Wiegner et al., 2021 [25]	USA	M	FIB, N, virus	Fractured basalt with unconfined aquifer, little soil	Not specified	Sewage is entering the groundwater at Puako and the underlying geology, rather than OSS type, primarily controls the speed at which sewage reaches the shoreline
Halla et al., 2022 [56]	Tanzania	P	FIB, N, Vibrio Cholerae	1-10m unconfined sand aquifer at top, 1-30m thick clay aquitard in the middle, 5-50m thick semi-confined aquifer at the bottom	2-4m	1m sand layer placed at bottom of pit reduced bacterial load better than 68m horizontal distance of alluvial sand aquifer. Genetic testing provided strong evidence human is source of cholera in shallow wells 7.3m horizontal distance from pit latrine
Mester et al., 2023 [57]	Hungary	S	N	Alluvial deposits on the riverbank	1-3m	A groundwater dome formed around the septic and high concentrations of COD and ammonia measured. On decommissioning, the groundwater dome rapidly disappeared but contamination reduced slowly with some elevated concentrations persisting for at least 5 years.
Pouye et al., 2023 [58]	Senegal	S	N	Quaternary sand aquifer containing sands and sandy clay	2m	Sharp rise in nitrate concentration in shallow groundwater during extreme rain events. No dilution effect observed during rains.

Notes: OSS type: P = pit or "combined function OSS"; S = septic or "separated function OSS"; U = unknown; M = Mixed of separated and combined function OSS.
Contaminants: FIB = Faecal Indicator Bacteria, N = nitrogen compounds, at least nitrate

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findings of all economic classifications captured in the "strong rating". Any differing implications due to economic status of the country are mentioned in the text.

Processes of pathogen removal have been quite well described. The formation of the biological layer is important and variable depending on conditions. Pathogen removal processes are influenced by ground conditions; in special cases pathogens have been detected at relatively long distances from OSS. The relationships between bacteria removal compared to virus removal and nitrate removal are complex.

These points are expanded below. We refer primarily to the papers rated as strong. When we draw on evidence from weak or not included studies this is stated in the text.

Biological layer. Although previous reviews stated the importance of the biological layer, it is only mentioned in seven of the strong studies [17, 18, 32, 35, 39, 41, 53], though its

Table 8. Country income, technology characteristics and method of studies included in the review.

	High income N˚(%)	Upper middle income N˚(%)	Lower middle income N˚(%)	Low income N˚(%)	Total N˚(%)
Technology Type					
Combined Functions /1	2 (3%)	3 (4%)	9 (13%)	1 (3%)	15 (22%)
Separated Functions /2	33 (49%)	2 (3%)	1 (1%)	0 (0%)	36 (54%)
Uncertain	2 (3%)	1 (1%)	6 (9%)	2 (3%)	11 (16%)
Mixed technologies	1 (1%)	1 (1%)	3 (4%)	0 (0%)	5 (7%)
Method					
Strong studies	27 (40%)	4 (6%)	7 (10%)	0 (0%)	38 (57%)
Weak studies	11 (16%)	3 (4%)	12 (18%)	3 (4%)	29 (43%)
Total	38 (57%)	7 (10%)	19 (28%)	3 (4%)	67 (100%)

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existence has been confirmed in several studies outside the scope of this review, such as a recent paper by Knappe, Somlai [59] and is discussed by Beal, Gardner [60] in their review of soil absorption systems. None of the studies attempted to directly measure pathogen reduction across the biological layer, although several authors provided indirect evidence that it is important. Caldwell [17] observed increased pathogen removal after a period of seven months operation and attributed that to development of the biological layer, and similarly Dyer [32] observed contamination extending several metres from a new latrine then retreating after

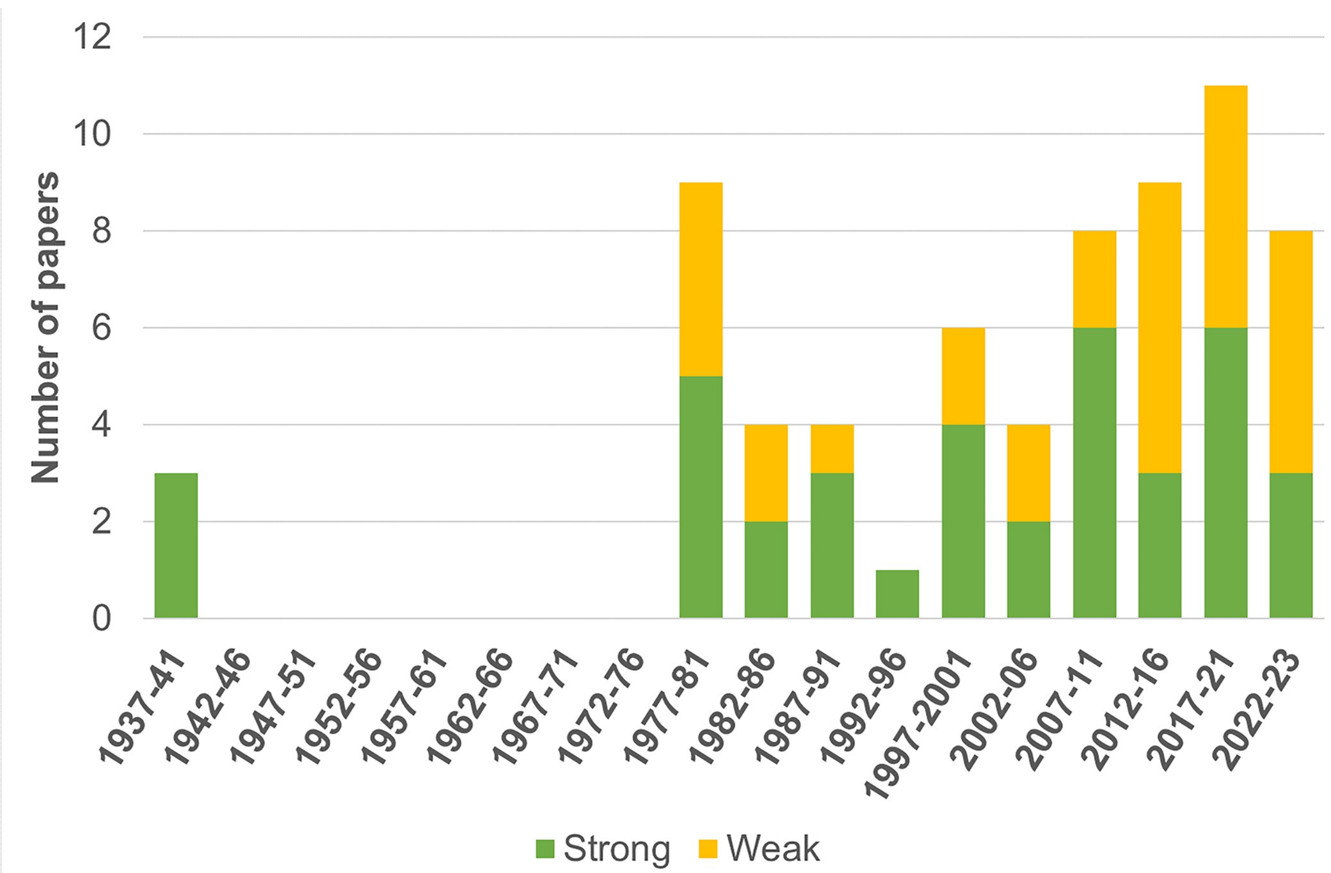

Fig 4. Papers by year of publication (in 5-year blocks, year is first year of block).

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Table 9. Characteristics of studies included in the review with strength of method.

	Strong studies N˚(%)	Weak studies N˚(%)	Total N˚(%)
Type of Study			
Cross Sectional	20 (30%)	15 (22%)	35 (52%)
Longitudinal	18 (27%)	14 (21%)	32 (48%)
Pathways considered			
Aquifer only	36 (53%)	18 (26%)	54 (79%)
Aquifer and localised	2 (7%)	8(13%)	14 (21%)
Contaminant observed			
Faecal indicator bacteria	28	19	47
Viruses	9	4	13
Nitrogen	22	15	37

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some months and attributed this to biological layer formation / soil clogging. In a case where septic tanks were only used seasonally; elevated faecal indicator bacteria (FIB) were detected in groundwater. Upon digging up the leach field no biological layer could be observed, and the authors concluded that seasonal use meant a biological layer did not adequately form and the lack of this layer reduced pathogen removal compared to what should have been expected given 1.7m of unsaturated sand and gravel [41]. The data compiled by Pang [7] shows higher removal rates in the soil layer which was defined as the biologically active ground layer so might support the importance of the biological layer. In 2008 and 2011, disease outbreaks affecting hundreds of people were reported in the United States following the use of newly constructed septic systems [48, 52]. The possibility that the biological layer may not have had adequate time to form was not considered in these studies but is a plausible explanation.

Conditions for effective pathogen removal. We examined the strong papers to understand the conditions where effective pathogen removal was achieved. An unsaturated zone of varying depths and soil characteristics caused attenuation of microbial organisms to negligible quantities in most of the strong studies. Soil conditions where this was achieved were described in ten of the strong studies as: fine gravel to clayey unconsolidated soils over rock formation [17]; fine to coarse loamy soils [35]; sandy soils, loamy sands and sandy loams [39, 40]; thin sands and clays overlying a karst aquifer [24]; clayey silty and sandy gravel soils [50]; coarse sand to gravel soils with traces of silt and clay [51]; silty sand, dense gravel and stiff sandy clay soil (residual granite) [55]; sandy permeable sediments and fine river sediments [10, 17, 24, 35, 39, 40, 50, 51, 55]. The 'strong' rated papers do not use a standard method of reporting soil structure. Most studies describe the structure using the relative content of clay, sand, silt and loam with little or no data provided on other soil properties that affect contaminant movement such as hydraulic conductivity, permeability and porosity. These studies all report reduction of FIB to below or near detection limits after travel distances ranging from as little as 1.2m to 10m [17, 32, 35, 50].

Two strong studies seemed to suggest longer travel distances in an unsaturated vadose zone than reported in the majority of the strong studies. The two studies were conducted in soils described as coarse-grained beach soils with well sorted medium sands [41] and sandy loams, silty loams, loamy sands and gravelly silty loams [38]. Chen [38] found high FIB concentrations were detected at 30.5m horizontal distance in 4 of 17 boreholes while investigating septic tank disposal systems, although limited data was provided on ground conditions. Postma, Gold [41] found a travel distance of about 6m in a seasonally used septic absorption system but as discussed above, attributed this to a lack of a biological layer due to seasonal use.

Conditions that impaired pathogen removal. Groundwater levels near, at or above the bottom of the pit or leach field were shown to increase the horizontal travel distances of pathogens when compared to unsaturated conditions in eight studies [17, 18, 33, 35, 40, 42, 50, 56]. The effect of saturated conditions was mainly examined by sampling contaminants over wet and dry seasons and/or sampling at locations with varying groundwater levels. Cogger, Hajjar [40] reported high bacterial counts while the water table was within 0.3m of a septic system and low counts during the dry season when the water table was 0.9m deep. There were cases where faecal indicator bacteria were only detected during the periods when the water table was high [35] indicating impairment of the OSS performance under these conditions. This observation was further emphasized by another study conducted on very shallow aquifers where the groundwater quality was found to be similar to soak pit effluent quality [42].

Water contained in the pores of saturated soils appears to be the medium for travel of soluble contaminants resulting in greater travel velocities and distances. Movement occurs in the direction of the groundwater flow which is likely to follow the gradient of the land surface in high water table areas [18]. The occurrence of a very thin vadose layer (<0.5m) under septic systems resulted in a lower vertical movement of bacteria compared to lateral movement. A study conducted over a 0.15m thick vadose zone in sandy clay soils reported lateral bacteria travel distances of 15.25m in the direction of the water gradient [33]. Where there is no water gradient, vertical percolation dominates [35]. Maximum travel velocity of 0.7m/d for contaminants was reported during the monsoon season in sandy silty soils where the ground was completely saturated [50].

Varying ground conditions caused by seasonal weather changes directly impact removal of contaminants. Frequently, though not always, authors reported increased concentrations of pathogens in groundwater receptors during wet seasons. The possible reasons for this include:

- Raised groundwater table reducing (or eliminating) the thickness of the unsaturated zone
- Increased water volumes flowing through the ground material causing flushing of pathogens from ground material and/or higher velocities leading to longer travel distances before complete pathogen die off.

Of the six strong papers that looked more specifically at rainfall events rather than seasonal variation, three showed a correlation between events and increased pathogen levels in monitoring bores, whereas two found no such correlation and one, Pouye, Cissé Faye [58] looked only at nitrogen. One paper stated rainfall had caused a temporary increase in FIB but did not provide data [40]. Keegan, Kilroy [53] found in one site rainfall increased pathogens while in their other site it decreased pathogens, though only in nearby sampling sites and no effect was seen in more distant groundwater bores. They suggested that the site where pathogens increased was one with a higher proportion of clay particles and rainfall may have washed out some pathogens that were attached to the clay. The other site was gravel with very little silt/clay and so may have had little pathogen removal occurring due to adsorption and so dilution from rainfall events was a bigger factor. This highlights the complexity of pathogen removal in differing ground conditions making it very difficult to be definitive about the impact of rainfall events in any given location.

Where the soils are highly permeable (such as in coarse sands and gravels), bedrocks are fractured or karst formations, pathogen transportation occurs over much longer distances as shown in eight strong papers. Evidence of flow in karst aquifers was found to be complex. It can be through the conduits in karst formation, or through unconsolidated sediments also known as matrix flow. Flow appeared to bypass one well in close proximity to the OSS while tracer was found in a well further down showing that there are possibilities of arrival at a well through multiple pathways [49]. There are cases where attenuation to negligible levels was achieved in a karst aquifer but in this case the karst was overlain by 2-3m of clayey loam soil which likely was enough of a barrier to pathogen transport [24]. Another study found that a fractured karst bedrock under a layer of sandy loam allowed bacterial travel velocity of more than 8.2m/d to a 60m deep well [48]. Greater travel distances have been reported in a study done on fractured dolomite subsurface where a tracer injected into a septic system was observed to travel at a velocity of 31m/d [52]. In another study in fractured bedrock underlying clayey soils movement of about 30m/d was reported in saturated conditions [20]. The orientation of the bedrock also was also reported to affect the movement of contaminants. The existence of viral contamination in a well was attributed to a steep dip of bedrock beneath a septic leach field sloping towards the well under unsaturated conditions [27].

The occurrence of pure clay soils presents a unique situation. In wet conditions it acts as an aquitard meaning it will hold moisture and restrain movement, which can lead to overland flow of effluent [53]. In dry conditions, the clay shrinks and forms cracks which increase the risk of contamination [4]. Banerjee [50] tested two pits with a 0.5m clay envelope (51% clay, 44% silt, 5% sand) and found this prevented faecal coliform transmission. Across 12 sites, Banerjee [50] found increasing clay content in a sand/silt/clay soil decreased the horizontal travel distance of faecal coliforms.

Localised pathways. Quantifying the significance of localised pathways is challenging and this remains a major gap in the literature. Only two studies comment on localised pathways at all. Ravenscroft, Mahmud [10] observed lower levels of bacterial contamination in purposely constructed monitoring wells constructed between and downstream of the OSS, when compared to the levels found on the spouts of an in-use hand pump. They argued that this showed that contamination was arising at the pump spout due to localised pathways. Ravenscroft, Mahmud [10] estimated that the localised pathways were a more significant source of disease burden than the aquifer pathway. The only other strong paper that discussed localised pathways was Keegan, Kilroy [53] who simply observed effluent from a soakaway running across the surface during heavy rainfall and potentially entering a bore or well through gaps in the apron or pump.

Impact of OSS technology type. The type of OSS studied may have an impact on levels of contamination especially for microbial contaminants. The biological layer forms in response to organic matter in the effluent. Therefore, improving removal of organics through, for example, a more effective septic tank design or using an aerobic treatment stage before the leach field, likely reduces formation of the biological layer and this has been shown to be the case in a study not included in this review [59]. However, none of the included studies set out to establish microbial and nitrogen removal between different types of OSS under similar conditions and there is too much variability in the conditions of the various studies for us to be able to discern any difference due to technology type.

OSS density. It can be argued that an increase in OSS density increases the risks of groundwater contamination, even if ground conditions are near ideal such as a thick unsaturated zone and fine ground material. This is particularly relevant in lower income countries where use of onsite systems in higher density urban areas is more prevalent. While several papers found in the review use statistical correlation between latrine density or proxy measures and FIB find there is a correlation with high density being associated with higher FIB, these papers did not fit the SPR model as typically other contamination sources were not excluded and/or pathways not tracked. Amongst the strong papers included in the review, density is generally not considered and so from this review we have not made any conclusions about the link between OSS density and FIB in groundwater. A systematic review with a different approach would be required to attempt to establish such a link.

Hydraulic load fluctuations. None of the studies supported the idea that a sudden increase in hydraulic load might force effluent flows beyond the biofilm later resulting in increased pathogen concentrations in the groundwater. Mattioli, Benedict [27] investigated a norovirus outbreak affecting 179 people at a camp whose toilets were discharging effluent to a nearby leach field. The drinking water well they were using tested positive for norovirus and human microbial source tracking (MST) genetic marker. Fluctuations in hydraulic loading before and during the camping events could have influenced contaminant movement but the idea was not considered in the study. One study attempted to look at the impact of different sustained hydraulic loading rates by comparing two septic leach fields, but was ultimately inconclusive as other site factors confounded the results [40].

In 1938, Caldwell conducted another study where the moisture content in pit latrines was varied by the addition of water. The result was an increase in the distance of travel of bacteria to 2m compared to a dry pit distance of 0.3m [17, 18].

FIB versus virus transport. Given that the review by Pang [7] suggested virus and bacteria removal rates were similar, we examined the included studies to see if there was evidence of good correlation between FIB and virus transport and detection. Nine strong studies included virus and FIB data and the consensus is that there is no correlation between occurrence of viruses and FIB [24, 26, 36, 39, 43]. Viruses are smaller in size compared to FIB and this is assumed to be the reason they can pass more easily through the biological layer [39] and achieve greater distances in sub-surface material [43, 36].

Nitrate. The included papers are consistent with the view that, provided aerobic conditions in the sub-surface, ammonia will rapidly oxidise to nitrate. Nitrogen transformations were examined in 37 of the included papers, 22 of which were considered to have a strong methodology. Only one strong paper [34] had an example where nitrification did not occur and the authors attributed this to very wet conditions beneath the leach field resulting in inadequate aeration. Another strong study reported a sharp rise in nitrate concentrations in monitoring bores near a septic tank system during an extreme rainfall event which the authors attributed to flushing of nitrogen from the vadose zone with possible rapid nitrification [58] Groundwater nitrate concentrations exceeded WHO drinking water standards (11.3 mg/L as N or 50 mg/L as NO_3) in 13 of the 22 strong papers studying nitrogen.

We sought to assess the included literature for evidence that denitrification was the most significant cause of nitrate removal and thus whether it can be relied upon to eventually reduce groundwater nitrate concentrations. However, resolving whether observed reductions in nitrate as effluent moves away from an OSS are due to dilution in surrounding groundwater, denitrification or potentially uptake by surface vegetation is not straightforward and most papers did not attempt to do this. Only five of the strong papers made a clear case that they have observed nitrate removal through denitrification, while two strong papers showed nitrate persisting in groundwater with no observable removal by denitrification or any other means.

Even where the source of nitrate inputs is reduced or ceased, if the aquifer has a long residence time and does not have the conditions to enable denitrification, nitrates may persist at high levels. For example, one study outside the scope of our review looked at data spanning over 20 years for nitrates in the aquifers beneath Urânia, Brazil and developed a calibrated model which predicted it will take 30 to 40 years for nitrate concentrations in the aquifer to fall to drinking water standards in a situation where cesspits have now largely been replaced by sewers [61].

4. Significance and limitations

This is an update to previous reviews but the first to use the source-pathway-receptor (SPR) method. This robust search methodology provides a new systematic understanding of the current state of the literature. Some studies which provide useful contributions to our understanding but whose methods preclude the confirmation of the SPR are excluded (for example Knappe, Somlai [59] and Beal, Gardner [60]). Some research on this topic may be outside of the academic sphere (for example in technical reports and feasibility studies) and there may be some published in languages other than English.

5. Conclusions

The source-receptor-pathway model is important in understanding the dynamics of contaminant movement from OSS to groundwater. It enables a more precise understanding of the contamination that arises directly from OSS as compared to contamination that may be associated with other sources and pathways. The dynamics of contaminant travel are complex and highly context specific. Movement of effluent within the subsurface is influenced by environmental conditions such as weather and climate; social conditions such as population and OSS density; physical conditions including soil structure, moisture, porosity, permeability, tortuosity and continuity, groundwater level, velocity and direction, excreta/wastewater hydraulic loading rate and composition [4, 40]. This variability means simple siting guidelines based on horizontal separation are not reliable. Due to these complex dynamics future studies would benefit from considering the source-pathway-receptor approach to ensure that other potential contamination sources and pathways are included in analysis of groundwater contamination from onsite sanitation.

Though not always recognised in the literature, formation of a biological layer is important for removal of microbial pathogens. This layer takes months to form which impacts the performance of OSS that are new or subject to highly variable loading or sudden increases in hydraulic load.

Under ideal conditions of an unsaturated zone comprising fine material (sands, silts, loams with some clay content) with effluent moving along the aquifer pathway, and an OSS greater than around 6 months old with a consistent hydraulic load, FIB can be reduced to detection limits within under 10 metres distance. However, ideal conditions are very often not present. If the groundwater level is close to the OSS, certainly under 1m, FIB can be expected to travel in the direction of the groundwater movement for greater distances, though it is hard to predict how far. Fissured rocks and karst formations can allow FIB to travel much further with distances of 60m or more recorded. Understanding ground conditions remains essential when deciding on the appropriateness of OSS.

Contamination can occur via localised pathways, but these were not well investigated. Contribution of the ingress of contaminated surface water into faulty boreholes/wells is significant yet not adequately covered in the included literature. There is a need more research on localised pathways as it has been argued they cause more diarrhoeal disease burden compared to aquifer pathways [10].

The use of FIB to detect viral contamination remains risky as achieving FIB below detection level doesn't mean viruses are reduced to "safe" levels. Multiple studies showed the presence of viruses in the absence of FIB.

The review established that it is extremely difficult to eliminate the risk of groundwater contamination when OSS effluent is discharged into the subsurface. Generally, it seems unsafe to assume that contamination can be prevented in areas where the density of OSS is high, though further research is needed to determine what density of is too high for a given set of ground conditions. In such cases, it would seem prudent to consider a shift to sanitation technologies with significantly lower risks of contaminating groundwater coupled with the provision of viable and convenient alternatives to the use of shallow groundwater for drinking.

Reflections on systematic reviews

The extraction of data on a specific topic from existing published literature through a detailed screening and eligibility process allows creation of a detailed summary on what is known about the topic. Further, by critically examining the collected evidence, gaps in literature are easily identified and presented to researchers for further investigation. Although systematic reviews are extensively used in the medical discipline, they are very useful tools in building the body of knowledge in all academic disciplines including the engineering and environmental sciences as presented in this paper. A Prisma checklist was completed and is in supporting information S1 Checklist.

Supporting information

S1 Checklist. PRISMA checklist.
(DOCX)

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