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Review

Decontamination of environmental surfaces in hospitals to reduce hospital-acquired infections: a systematic review

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SUMMARY

Background: The impact of hospital surface decontamination on hospital-acquired infections (HAIs) remains uncertain. We assessed the effects of hospital surface decontamination, through cleaning, disinfection, or both, on patient-centred outcomes.
Methods: A systematic review of randomised controlled trials (RCTs) and quasi-RCTs was conducted following Cochrane/GRADE methods. Meta-analysis was not feasible because of few studies.
Results: We included 11 RCTs conducted between 2007 and 2017 in high-income countries. Seven had financial conflicts. At most one RCT provided data per review outcome. Certainty of evidence was very low across all comparisons: quaternary ammonium compound (QAC) versus detergent on HAIs (incidence rate ratio [IRR]: 0.95, 95% confidence interval [CI]: 0.69—1.31); probiotic versus detergent on HAIs (IRR 0.96, 95% CI: 0.69—1.32);

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infections
Copper
GRADE

phenolic versus detergent on HAIs (relative risk [RR]: 1.13, 95% CI: 0.57—2.24); QAC versus probiotic on HAIs (IRR: 1.00, 95% CI: 0.72—1.39); increased high-touch surface disinfection frequency on methicillin-resistant *Staphylococcus aureus* colonisation (odds ratio [OR]: 0.98, 95% CI: 0.58—1.66); ultraviolet light on colonisations by vancomycin-resistant enterococci (IRR: 1.00, 95% CI: 0.79—1.25) or *Clostridioides difficile* (IRR: 1.58, 95% CI: 0.97—2.58), or HAIs (IRR: 1.10, 95% CI: 0.48—2.51); copper surfaces on HAIs (RR: 0.64, 95% CI: 0.36—1.14), bloodstream infections (RR: 0.30, 95% CI: 0.08—1.05), or all-cause mortality (RR: 0.91, 95% CI: 0.63—1.33).

Conclusion: Evidence from RCTs on hospital surface decontamination and patient outcomes remains uncertain. These inconclusive findings on cleaning or disinfection do not indicate evidence of no effect but highlight the need for new RCTs.

Introduction

Hospital-acquired infections (HAIs) pose a global threat to patient safety and healthcare quality. The prevalence is typically below 10% in high-income countries but often exceeds 20% in low- and middle-income countries [1,2]. HAIs increase morbidity, mortality, disability, and healthcare costs. Frequent multi-drug-resistant organisms, such as methicillin-resistant *Staphylococcus aureus* (MRSA), complicate management [3].

Hospital environmental surfaces include medical equipment (e.g. haemodialysis knobs) and housekeeping surfaces (e.g. floors and keyboards). They can have minimal or frequent hand contact ('high-touch surfaces'). Environmental surfaces play a documented role in pathogen transmission in healthcare settings as pathogens can survive on hospital surfaces for days to months, recontaminate them rapidly after cleaning, and transfer them to patients or staff [4]. Occupying a space previously used by a colonised/infected patient increases the risk of infection [5]. Thus, effective environmental hygiene is essential for the prevention and control of HAIs.

Decontamination of environmental surfaces involves the removal or destruction of soil and pathogenic micro-organisms from the surfaces. The levels of decontamination are cleaning (water, mechanical action, and detergents), disinfection (chemical or physical methods), or sterilisation, the latter reserved for medical instruments. Examples of chemical disinfectants include quaternary ammonium compounds (QACs) and bleach (sodium hypochlorite). Physical disinfection is an emerging research area. Examples include no-touch disinfection methods based on ultraviolet light C (UV-C) radiation or hydrogen peroxide vapour (HPV) devices. Self-disinfecting surfaces such as copper have also received attention.

Cleaning alone can be adequate for routine decontamination. Enhanced cleaning uses additional interventions, such as increased frequency, or automated equipment, such as floor scrubbers. Terminal decontamination is performed in a room between occupying patients and is normally augmented with a disinfectant to ensure contamination removal before use by another patient.

Hospital surface decontamination faces challenges including inadequate cleaning, rapid recontamination, unforeseen transmission risks, and poor hand hygiene after surface contact [6,7]. Evidence comparing decontamination strategies is limited, probably explaining the heterogeneous practices across centres [8]. Moreover, reducing the surface microbial burden does not necessarily lead to fewer infections, leaving the clinical impact of decontamination uncertain [9]. Finally, disinfectants can harm health and the environment and promote antimicrobial resistance [10].

Given the clinical and economic burden of HAIs, there is an urgent need for effective, safe, and sustainable decontamination strategies, particularly in the post-COVID-19 era. This systematic review aimed to assess the effects of hospital surface decontamination, through cleaning, disinfection, or both, on HAIs.

Methods

To see the full section on methods, check the Supplement.

Study design

We followed Cochrane/GRADE methods [11,12], the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [13], and a pre-registered protocol [14]. Deviations from the protocol reflected updated systematic review methods (see Supplement).

Eligibility criteria

We included studies involving hospital patients of any age, sex, or gender identity, as well as staff, caregivers, and visitors. Other facilities (e.g. nursing homes) were excluded. Any decontamination method of hard surfaces was eligible. Antimicrobial treatment of textiles (e.g. clothing or bed linens) was excluded. Decontamination could involve cleaning alone or cleaning plus disinfection. Multi-component interventions were eligible only if decontamination was the primary component and co-interventions were balanced across groups. Any comparator was eligible.

Primary outcomes were hospital-acquired colonisation (only when admission screening was performed): HAIs; HAIs among staff, caregivers, or visitors; and adverse effects. Secondary outcomes were bloodstream infections (BSIs), all-cause mortality, HAI-related mortality, length of hospital stay, and resistance to antibiotics or disinfectants. Any follow-up period was accepted. We excluded studies assessing surface contamination exclusively.

We included randomised controlled trials (RCTs) and quasi-randomised controlled trials (Q-RCTs), regardless of the publication status or language.

Information sources

Information specialists searched MEDLINE, Embase, CENTRAL, CINAHL, and ProQuest Dissertations & Theses Global (until February 24th, 2025), Web of Science (3rd March, 2025), the British Nursing Index and Archive via ProQuest (February 29th, 2012), and OpenGrey (December 10th, 2020). No language, date, or setting restrictions were applied. We searched ClinicalTrials.gov and WHO International Clinical Trials Registry Platform (ICTRP) for ongoing or unpublished studies (3rd March, 2025). Full search strategies are provided in the Supplement.

We screened reference lists of the included studies, relevant reviews, and conference proceedings (2008—2024). We contacted authors of key papers for additional studies. We tracked included studies and relevant reviews in the ISI Science Citation Index. Retraction and errata were checked on article pages and in PubPeer and Retraction Watch. No separate searches for adverse effects were performed.

Study selection

We removed duplicates in EndNote (Clarivate) and imported unique records into Covidence (Veritas Health Innovation Ltd) for further deduplication and screening. Two reviewers (J.L.-A., M.M.-M., A.E.G.-V., L.O.C., E.J.T., and/or S.C.N.) independently screened titles/abstracts and full texts, resolving disagreements by consensus or a third reviewer. Trialists were contacted to clarify eligibility. For the excluded full texts, we recorded the main exclusion reason. Multiple reports from the same study were grouped, using the most complete report for data extraction.

Data extraction and risk of bias assessment

We extracted data in EPPI-Reviewer using a piloted form. One reviewer extracted data, and another checked it; discrepancies were resolved by consensus or a third reviewer. We contacted authors for clarification, checked for retractions or errata, verified numeric accuracy, and attempted to convert composite outcomes into eligible non-composite outcomes. Two reviewers independently assessed the risk of bias using the Cochrane Risk of Bias 2 tools for individually randomised parallel-group and cluster RCTs [11]. Disagreements were resolved by consensus or by a third reviewer.

Effect measures, data analysis, and synthesis methods

We predefined comparisons and grouped studies by technique, product, area, timing (daily or terminal), equipment, frequency (standard or increased), and target surface (e.g. high-touch surfaces). Because few studies were available, we could not perform meta-analyses, assess heterogeneity or publication bias, or perform subgroup or sensitivity analyses. We present results as risk ratios (RRs), odds ratios (ORs), or incidence rate ratios (IRRs) with their 95% confidence intervals (CIs), calculated using RevMan Web or OpenEpi. We report both the relative and absolute effects. Absolute effects per 1000 patients or per 1000 patient-days were calculated using GRADEpro or MS Excel and interpreted considering predefined thresholds (see Supplement). Unit-of-analysis errors were identified when analyses ignored data clustering and corrected by inflating standard errors.

Study characteristics are summarised in tables and a narrative synthesis, with descriptive statistics generated in MS Excel. Certainty of evidence was assessed using GRADE [12].

Results

Results of the searches and study selection

The searches until 3rd March, 2025, identified 10,528 records. After removing 2064 duplicates, 8464 records were screened. Of these, 8153 were excluded by the title and abstract. We retrieved 311 reports for full-text assessment and excluded 256 (82%). The most frequent reason for exclusion ($N = 28$) was the inability to isolate decontamination effects from broader infection control bundles. The Supplement lists exclusion reasons for studies that may appear eligible. The review included 11 studies [15—25], described in 51 reports. We also identified four ongoing trials [26—29]. PRISMA flowchart is shown in Figure 1.

Characteristics of the included studies

Tables I and II detail the characteristics of the eleven included studies [15—25].

Study methods

Eight studies were cluster cross-over cross-sectional randomised controlled trials (CRXO-RCTs), and three were individually randomised parallel randomised controlled trials (i-RCTs). Only six CRXO-RCTs included washout periods. Sample sizes ranged from 70 to 21,395 patients, and two trials did not report sample sizes. Seven studies had financial conflicts of interest.

Setting and epidemiological context

The studies were published between 1976 and 2024, with seven published after 2012. Nine trials started recruitment between 2007 and 2017; two were conducted before 1987. The study duration ranged from six to 33 months. Nine studies were conducted in North America and two in Europe. All trials were conducted in urban academic hospitals in high-income countries. Most trials were single-centre studies ($N = 7$) at hospitals with more than 500 beds (N=7).

Settings included wards ($N = 5$), intensive care units (ICUs) ($N = 3$), both ($N = 2$), or operating rooms ($N = 1$). Three studies targeted rooms with known colonised or infected patients. Two were prompted by high infection levels or outbreaks. Colonisation pressure was reported in only one study and was high [18].

Participants' baseline characteristics

Mean patient age ranged from 53 to 68 years when reported. All trials included both sexes, with 52—63% males. Race was reported in three studies: white participants predominated in two. No study reported gender identity or socioeconomic status. Patient groups varied: mixed medical and surgical ($N = 5$), medical only ($N = 1$), and surgical only ($N = 1$). One study focussed on solid organ transplant recipients. Six studies involved non-ICU settings, three ICUs, and two mixed settings. Comorbidities were generally poorly reported.

Interventions and comparators

Table II summarises the main interventions and co-interventions. Most studies focussed on the product used

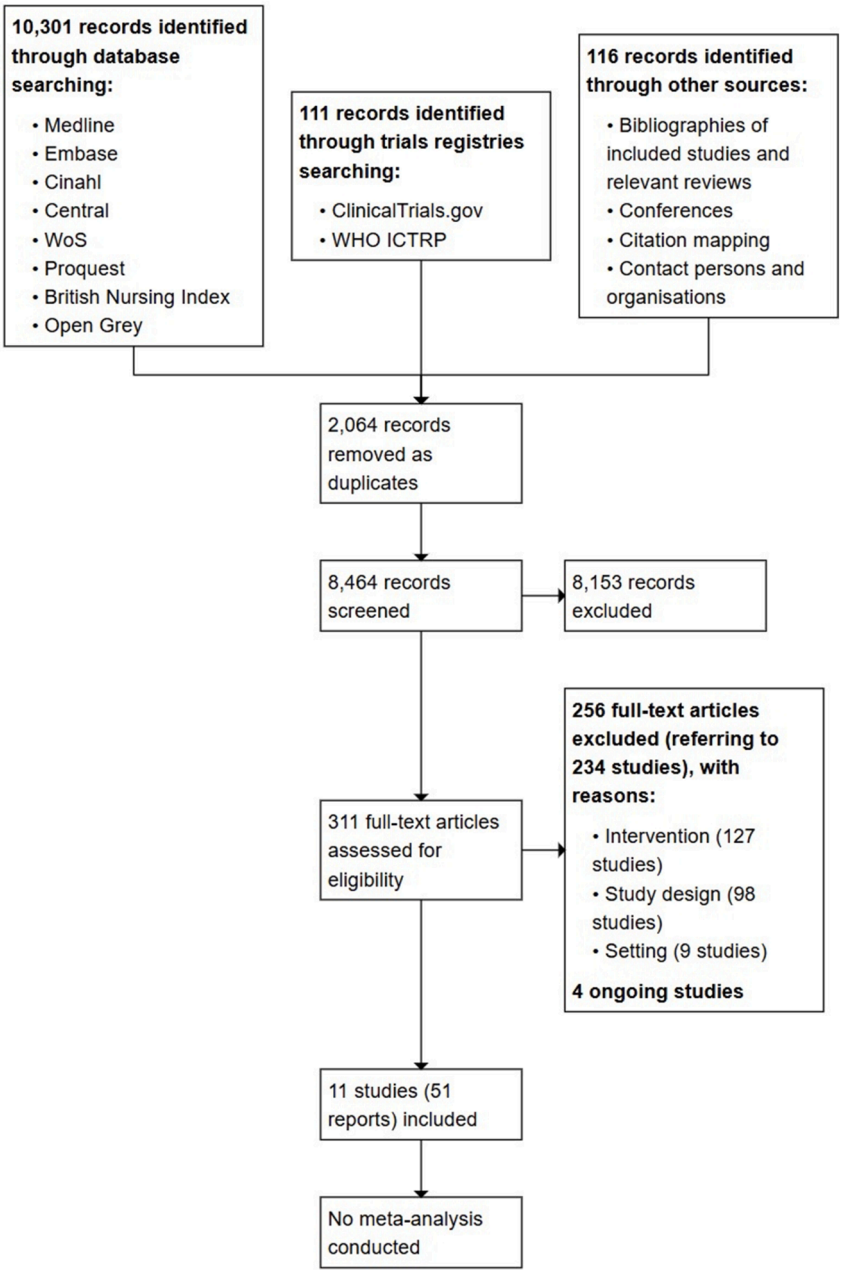

Figure 1. Flow chart. WHO, World Health Organization.

($N = 7$), followed by increasing high-touch surface decontamination frequency ($N = 3$) or reducing floor decontamination frequency according to expected contamination levels ($N = 1$). Interventions occurred during routine decontamination ($N = 6$), terminal decontamination ($N = 2$), or both ($N = 3$). Intervention periods ranged from 7 days to 24 months, with nine lasting at least nine months, supporting assessment beyond seasonal effects.

Most studies evaluated manual decontamination ($N = 8$), followed by no-touch techniques ($N = 3$) and antimicrobial surfaces ($N = 1$). Manual disinfectants included QACs ($N = 4$), bleach ($N = 1$), bleach specifically for *Clostridioides difficile* rooms ($N = 2$), phenolics ($N = 3$), probiotics ($N = 1$), improved hydrogen peroxide (IHP) ($N = 1$), and ultramicrofibre cloths with copper-based formulations ($N = 1$). No-touch techniques included UV-C light ($N = 2$) and pulsed xenon UV ($N = 1$). One trial assessed copper surfaces. Comparators included another active intervention ($N = 4$), standard practice ($N = 1$), detergents ($N = 2$), sham procedures ($N = 2$), or no intervention (N=3).

Review outcomes

Four studies did not report any outcomes of interest in our review [15,16,19,24]. The remaining seven studies reported at least one [17,18,20–23,25]. No study reported HAIs among staff, caregivers, or visitors; HAI-related mortality; or resistance to antibiotics or disinfectants. See Table II.

Table I
Characteristics of included studies

No. of included studies	Included studies										
	BETR [15]	Boyce [16]	Danforth [17]	LAMP [18]	Hess [19]	KARMIN [20]	Kundrapu [21]	Rock [22]	Salgado [23]	Weber [24]	Wilson [25]
Publication date	2017	2017	1987	2024	2013	2023	2012	2022	2013	1976	2011
Review outcome[a]	X	X	✔	✔	X	✔	✔	✔	✔	X	✔
Study methods											
Design type	CRXO-RCT	CRXO-RCT	CRXO-RCT	CRXO-RCT	CRXO-RCT	CRXO-RCT	i-RCT	CRXO-RCT	i-RCT	i-RCT	CRXO-RCT
Wash-out period, weeks	4	Absent	Absent	24	4	4	NA	5	NA	NA	1
Nr. of arms (allocation ratio)	4 (1:1:1:1)	2 (1:1)	2 (1:1)	2 (1:1)	2 (1:1)	3 (1:1:1)	2 (1:1)	2 (1:1)	2 (1:1)	2 (1:1)	2 (1:1)
Nr. of patients[b]	21,395	—	5883	19,413	190	13,896	70	7172	614	—	2583
Conflict of interest[c]	Present	Present	—	Present	Present	Not present	Present	Present	Present	—	Not present
Setting											
Country	USA	USA	Canada	USA	USA	Germany	USA	USA	USA	Canada	UK
Nr. of hospitals/study	9	1	1	2	1	1	1	1	3	1	2
Nr. of beds/hospital	148; 950	—	930	273; 334	757	≈ 3100	215	1059	98; 460; 660	—	665; 839
Hospital area	Ward	ICU/ward	Ward	ICU/ward	ICU	Ward	Ward	Ward	ICU	OpR	ICU
Target rooms	C/I	Any	Any	Any	C/I	Any	C/I	Any	Any	Any	Any
Epidemiological context											
High infection levels[d]	—	—	—	✔	—	X	—	—	—	—	✔
Colonisation pressure[e]	—	—	—	High	—	—	—	—	—	—	—
Baseline characteristics											
Age, mean (median), years	58 (—)	—	—	58 (—)	53 (—)	— (61)	54 to 68 (—)	—	60 (—)	—	59 (—)
Sex, % male	52	—	—	52	63	53	—	—	63	—	57
Gender identity, % men	—	—	—	—	—	—	—	—	—	—	—
Race, % of white patients	64	—	—	9	—	—	—	—	64	—	—
Socioeconomic status, % high	—	—	—	—	—	—	—	—	—	—	—
Patients' case mix[f]	—	Medical	—	—	Mixed	Mixed	—	Mixed	Mixed	Surgical	Mixed
Intensive care	X	Mixed	X	Mixed	✔	X	X	X	✔	X	✔

CRXO-RCT, cluster cross-over cross-sectional randomised controlled trial; i-RCT, individually randomised parallel randomised controlled trial; NA, not applicable; Nr, number; ICU, intensive care unit; OpR, operating room; C/I, rooms with colonised or infected patients.

[a] Studies presenting data for at least one review outcome.

[b] Observed samples sizes for the review outcomes.

[c] Authors reporting employment, grants, consultancy, or funding ties with organisations that had a financial interest in the evaluated products.

[d] Study prompted by high infection levels or recent outbreak.

[e] Colonisation pressure: proportion of patients already colonised or infected.

[f] Medical, surgical, or mixed (both medical and surgical) patients.

Table II
Characteristics of the interventions and review outcomes informed in the included studies

Study	Aspect evaluated Area; surface; timing	Intervention period	Technique: intervention (compliance %)	Technique: Comparator (compliance %)*	Co-interventions reported in both arms	Review outcomes								
						A	B	C	D	E	F	G	H	I
BETR [15]	■ Substance ■ Ward; All; T	24 months	QAC (or bleach for rooms with CD) (100%)	Bleach (96%)	a[k,l]-c-d-e-f-g-h-i-j									
			QAC (or bleach for rooms with CD) (93%) & UV-C (92%)	Bleach (96%)										
			QAC (or bleach for rooms with CD) [2] (93%) & UV-C (92%)	QAC (or bleach for rooms with CD) (100%)										
			Bleach (99%) & UV-C (91%)	Bleach (96%)										
			Bleach (99%) & UV-C (91%)	QAC (or bleach for rooms with CD) (100%)										
			QAC (or bleach for rooms with CD) (93%) & UV-C (92%)	Bleach (99%) & UV-C (91%)										
Boyce [16]	■ Substance ■ Ward/ICU; All; R/T	12 months	QAC (or bleach for rooms with CD) (95%)	IHP (including CD rooms, bleach not used) (94%)	a-b-c-d-e-f-g-h-i-j									
Danforth [17]	■ Substance ■ Ward; Floors; R	6 months	Phenolic disinfectant	Detergent	a[?]-b-c-d-e-f-g -h- i-j		✔		✔					
KARMIN [20]	■ Substance ■ Ward; All; R	12 months	QAC/Alcohol/Amine disinfectant (97%)	Detergent (96%)	a-b-c-d-e-f-g- h-i-j		✔							
			Probiotic disinfectant (97%)	Detergent (96%)										
			QAC/Alcohol/Amine disinfectant (97%)	Probiotic disinfectant (97%)										
Kundrapu [21]	■ Target HTS ■ Ward; HTS; R	≤ 7 days or until patient's discharge	Adding phenolic disinfectant (daily)	No intervention	a[?]-b[n] -c-d-e-f-g-h- i-j								✔	
Wilson [25]	■ Target HTS ■ ICU; HTS; R	12 months	Adding ultramicrofibre copper biocidal twice/day	No intervention	a[o,p]-b-c-d-e-f-g-h- i j	✔[s]								
Hess [19]	■ Target HTS ■ ICU; HTS; R	≈ 9 months	1 extra QAC disinfection/day (100%)	Sham intervention (26%)	a[k]-b-c-d-e-f-g-h-i-j									
Weber [24]	■ Reducing frequency ■ OpR; Floors; R	9 months	Phenolic between dirty surgery	Phenolic between all surgeries	a[q]-b-c-d-e-f-g-h-i-j									
LAMP [18]	■ Substance ■ Ward/ICU; All; T	24 months	Adding Pulsed xenon UV (90%)	Sham intervention (90%)	a b-c-d-e-f- ~~g-h~~ i ~~j~~		✔							
Rock [22]	■ Substance ■ Ward; All; R/T	24 months	Adding UV-C light (compliance varied by hospital unit)	No intervention	a- b-c-d-e-f-g-h- i-j	✔[t,u]								
Salgado [23]	■ Substance ■ ICU; HTS; R/T	11 months	Copper surfaces (47%)	Standard surfaces (87%)	a[k,l,r] b[?]-c-d-e-g -h-i-j		✔		✔	✔		✔		

Review outcomes: A: hospital-acquired colonisations; B: healthcare-associated infections; C: healthcare-associated infections among staff, caregivers, or visitors; D: bloodstream infections; E: all-cause mortality; F: healthcare-associated infections—related mortality; G: length of hospital stay; H: adverse effects; I: resistance to antibiotics or to disinfectants.
T, terminal decontamination, that is, decontamination of a room between occupying patients, also called deep decontamination; QAC, quaternary ammonium compound; CD, *Clostridioides difficile*; UV-C, no-touch disinfection with ultraviolet-C radiation; ICU, intensive care unit; R, routine decontamination, that is, daily decontamination without terminal decontamination that is applied in the routine care of all patients at all times; IHP, improved hydrogen peroxide; HTS, high-touch surface; OpR, operating room.
a: routine touch decontamination of all rooms; b: terminal touch decontamination; c: gloves; d: hand hygiene; e: monitoring and feedback to the provider on decontamination compliance; f: monitoring and feedback on hand hygiene compliance; g: methicillin-resistant *Staphylococcus aureus* (MRSA) or vancomycin-resistant enterococcus (VRE) screening; h: MRSA eradication; i: patient's isolation; j: infection surveillance; K: QAC disinfectant; l: bleach in rooms with *Clostridioides difficile*; m: for all rooms, including those with patients with *C. difficile*; n: bleach; o: detergent; p: isopropyl alcohol spray; q: phenolic disinfectant; r: CaviCide (Metrex) for spot cleaning of rooms and equipment (alcohol plus a QAC); ?: product not reported; s: hospital-acquired colonisations by MRSA; t: hospital-acquired colonisations by vancomycin-resistant *Enterococci*; u: hospital-acquired colonisations by *C. difficile*.

We identified four unit-of-analysis issues (see Supplement). First, four studies used statistical methods that ignored dependency in infection/colonisation data, likely underestimating variability [17,18,22,23]. Second, two CRXO trials [17,18] ignored within-cluster correlations; we corrected this by inflating the standard errors. Third, one study [17] reported HAIs/BSIs as dichotomous outcomes without clarifying handling of recurrent events. Fourth, the trial registration of Salgado *et al*. planned HAIs as the outcome [30], but the article reported 'HAI and/or colonisation' and 'HAI only', omitting patients with both [23]. Following the approach described in the study by Harbarth [31], we re-analysed HAIs as patients with at least one HAI.

Characteristics of the ongoing studies

We classified four RCTs [26—29] as ongoing because we found no published results. These trials planned to evaluate HPV [26], copper surfaces [27], organosilane [29], and engineered rooms [28] to prevent HAIs. The expected completion dates ranged from 2017 to 2024, except ACTRN12614000034639 [26], which did not report its end date. See Supplement.

Effects of interventions

We present the results only for outcomes with data from at least one study. See Table III. We report unit-of-analysis errors when present and sensitivity analyses when they altered effect direction or statistical significance. See detailed risk of bias assessments in Supplement.

a. Manual touch decontamination

Four RCTs [15—17,20] evaluated manual touch decontamination products, and only two [17,20] reported review outcomes (HAIs and BSIs). Three studies were conducted in wards [15,17,20] and one in mixed ward/ICU settings [16]. The Benefits of Enhanced Terminal Room (BETR) multicentre, four-arm trial [15] and Boyce QAC versus IHP trial [16] were eligible but did not report any review outcomes.

Comparison 1: QAC disinfectants versus detergents for routine decontamination in the hospital ward

One RCT [20] addressed this comparison and presented data for one review outcome.

Hospital-acquired infections

The evidence is very uncertain regarding the effect on HAIs (IRR: 0.95, 95% CI: 0.69 to 1.31; 1 RCT [20]; absolute rate difference [ARaD]: −1 infection per 1000 patient-days, 95% CI: −5 to 5; very low-certainty evidence).

Comparison 2: Probiotic disinfectants versus detergent for routine decontamination in the hospital ward

One RCT [20] addressed this comparison and presented data for one review outcome.

Hospital-acquired infections

The evidence is very uncertain regarding the effect on HAIs (IRR: 0.96, 95% CI: 0.69 to 1.32; 1 RCT [20]; ARaD: −1 infection per 1000 patient-days, 95% CI: −5 to 5; very-low-certainty evidence).

Comparison 3: Phenolic disinfectants versus detergent for routine decontamination in the hospital ward

One RCT [17] published in 1987 addressed this comparison and presented data for one review outcome.

Hospital-acquired infections

The evidence is very uncertain regarding the effects on HAIs (relative risk [RR]: 1.13, 95% CI: 0.57 to 2.24; re-analysed due to unit-of-analysis error; 1 RCT [17]; absolute risk difference [ARD]: 5 ‰, 95% CI: − 17 ‰ to 50‰; very-low-certainty evidence).

Bloodstream infections

Evidence about the effects on BSIs is very uncertain. Danforth [17] reported that the incidence of BSIs ranged from 0% to 1.3% in eight wards using phenolic disinfectant and from 0% to 1.2% in eight wards using detergents. Due to incomplete reporting, we could not analyse the data.

Comparison 4: QAC disinfectants versus probiotic disinfectants for routine decontamination in the hospital ward

One RCT [20] addressed this comparison and presented data for one review outcome.

Hospital-acquired infections

The evidence is very uncertain regarding the effects on HAIs (IRR: 1.00, 95% CI: 0.72 to 1.39; 1 RCT [20]; ARaD: 0 infection per 1000 patient-days, 95% CI: −5 to 7; very low-certainty evidence).

b. Increasing the frequency of manual touch decontamination of high-touch surfaces

Three RCTs assessed increasing the frequency of routine disinfection of high-touch surfaces [19,21,25]. Only Wilson [25] and Kundrapu [21] reported review outcomes. Hess [19] evaluated the daily additional disinfection of high-touch ICU surfaces with QACs, but outcomes (healthcare workers' gown and glove contamination) were ineligible. Wilson [25] added twice-daily ICU disinfection of high-touch surfaces using ultramicrofibre cloths with a copper-based biocide. Both arms underwent routine decontamination of high-touch surfaces with detergent and isopropyl alcohol spray. Kundrapu [21] applied daily morning disinfection of high-touch surfaces using peracetic acid. Both arms applied routine decontamination of high-touch surfaces only when visibly soiled, with unspecified products.

Comparison 5: Increased versus standard frequency of routine disinfection of high-touch surfaces

Hospital-acquired colonisations (MRSA)

The evidence is very uncertain regarding the effects on MRSA hospital-acquired colonisations (OR: 0.98, 95% CI: 0.58 to

Table III
Effects of decontamination of hospital environmental surfaces

Outcome	Nr. of studies (Nr. of participants) Mean arm follow-up	Relative effect (95% CI) UAE	Control risk for moderate risk scenario	Absolute effect (95% CI)	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Certainty of the evidence
Comparison 1: QAC disinfectants versus with detergents for routine decontamination in the hospital ward										
Hospital-acquired infections	1 CRXO-RCT [20] (9243) 33,168 patient-days	IRR: 0.95 (0.69—1.31)	17 per 1000 patient-days	−1 per 1000 patient-days (− 5 to 5)	Not serious	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Comparison 2: Probiotic disinfectants versus detergent for routine decontamination in the hospital ward										
Hospital-acquired infections	1 CRXO-RCT [20] (9361) 33,150 patient-days	IRR: 0.96 (0.69—1.32)	17 per 1000 patient-days	−1 per 1000 patient-days (− 5 to 5)	Not serious	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Comparison 3: Phenolic disinfectants versus detergent for routine decontamination in the hospital ward										
Hospital-acquired infections	1 CRXO-RCT [17] (5883) —	RR: 1.13 (0.57—2.24) UAE[b]	40 per 1000 patients	5 per 1000 patients (− 17 to 50)	Very serious[c]	Not serious	Serious[d]	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Bloodstream infections	1 CRXO-RCT [17] (−) —	Range of BSI incidence in phenolics wards: 0% —1.3%. Range of BSI incidence in detergents wards: 0%—1.2% Reporting incomplete: we could not analyse the data.			Very serious[e]	Not serious	Serious[d]	Extremely serious[f]	Not serious	⨁◯◯◯ Very low
Comparison 4: QAC disinfectants versus probiotic disinfectants for routine decontamination in the hospital ward										
Hospital-acquired infections	1 CRXO-RCT [20] (9188) 32,614 patient-days	IRR: 1.00 (0.72 —1.39)[g]	17 per 1000 patient-days	0 per 1000 patient-days (− 5 to 7)	Not serious	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Comparison 5: Increased versus standard frequency of routine disinfection of high-touch surfaces										
Hospital-acquired colonisations (MRSA)	1 CRXO-RCT [25] (2504) —	OR: 0.98 (0.58—1.66)	150 per 1000 patients	−3 per 1000 patients (− 57 to 77)	Serious[h]	Not serious	Serious[i]	Extremely serious[j]	Not serious	⨁◯◯◯ Very low
Adverse effects in patients	1 i-RCT [21] (70) Mean: 4.9—6.8 days	Patients reported no adverse effects during the use of the peracetic acid-based disinfectant.			Very serious[k]	Not serious	Not serious	Extremely serious[l]	Not serious	⨁◯◯◯ Very low
Adverse effects in staff	1 i-RCT [21] (−) —	Nursing staff reported no complaints about the peracetic acid-based disinfectant.			Very serious[k]	Not serious	Not serious	Extremely serious[m]	Not serious	⨁◯◯◯ Very low
Comparison 6: Adding UV light to standard practice versus standard practice alone										
Hospital-acquired colonisations (VRE)	1 CRXO-RCT [22] (7172) 22,937	IRR: 1.00 (0.79—1.25)	18 per 1000 patient-days	0 per 1000 patient-days (− 4 to 5)	Serious[n]	Not serious	Not serious	Not serious[o]	Not serious	⨁⨁⨁◯ Moderate

Hospital-acquired colonisations (CD)	1 CRXO-RCT [22] (7172) 13,116[p]	IRR: 1.58 (0.97–2.58)	10 per 1000 patient-days	6 per 1000 patient-days (0–16)	Serious[n]	Not serious	Not serious	Very serious[q]	Not serious	⨁◯◯◯ Very low
Hospital-acquired infections	1 CRXO-RCT [18] (19,413) 90,477	IRR: 1.10 (0.48–2.51) UAE[r]	17 per 1000 patient-days	2 per 1000 patient-days (− 9 to 26)	Serious[s]	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Comparison 7: Copper-surfaces versus standard surfaces in the ICU										
Hospital-acquired infections	1 i-RCT [23] (614) Median: 4 days	RR: 0.64 (0.36–1.14) UAE[t]	240 per 1000 patients	−86 per 1000 patients (− 154 to 34)	Very serious[u]	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Bloodstream infections	1 i-RCT [23] (614) Median: 4 days	RR: 0.30 (0.08–1.05)	80 per 1000 patients	−56 per 1000 patients (− 74 to 4)	Very serious[v]	Not serious	Not serious	Extremely serious[w]	Not serious	⨁◯◯◯ Very low
All-cause mortality	1 i-RCT [23] (614) Median: 4 days	RR: 0.91 (0.63–1.33)	150 per 1000 patients	−13 per 1000 patients (− 56 to 50)[x]	Very serious[y]	Not serious	Not serious	Extremely serious[a]	Not serious	⨁◯◯◯ Very low
Length of hospital stay	1 i-RCT [23] (614) Median: 4 days	Statistical analysis showed no difference in ICU LOS between groups (median 4 days in both; $P = 0.74$)			Very serious[z]	Not serious	Not serious	Extremely serious [aa]	Not serious	⨁◯◯◯ Very low

CI, confidence interval; UAE, unit-of-analysis error; QAC, quaternary ammonium compound; CRXO-RCT, cluster cross-over cross-sectional randomised controlled trial; IRR, incidence rate ratio; —. not reported; RR, relative risk; BSI, bloodstream infection; OR, odds ratio; i-RCT, individually randomised parallel randomised controlled trial; UV, ultraviolet; VRE, vancomycin-resistant *enterococcus*; CD, *Clostridioides difficile*; ICU, intensive care unit; LOS, length of hospital stay.

[a] Downgraded three levels for extremely serious imprecision: 95% CI of the absolute effect includes both large benefit and large harm (crosses > three thresholds).

[b] Corrected for unit-of-analysis error. First, the original χ^2 test assumed independence of events. Second, the original test did not account for cluster or cross-over correlations of CRXO designs. We applied an approximate analysis by inflating the standard error with the design effect. The revised estimate (RR: 1.13, 95% CI: 0.57 to 2.24), was similar to the original (RR: 1.12, 95% CI: 0.94 to 1.35).

[c] Downgraded two levels for very serious risk of bias. High risk due to deviations from intended interventions, missing outcome data, and outcome measurement. Some concerns about randomisation and selective outcome reporting.

[d] Downgraded one level for serious indirectness: study conducted before 1987 (epidemiological context and CDC surveillance definitions for hospital-acquired infections [HAIs] do not apply).

[e] Downgraded two levels for very serious risk of bias. High risk due to deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting. Some concerns about randomisation.

[f] Downgraded three levels for extremely serious imprecision. No 95% CI was presented.

[g] Calculated by the reviewers.

[h] Downgraded one level for serious risk of bias. An outbreak of multi-drug-resistant *Acinetobacter baumannii* occurred before and during the study, affecting only the standard cleaning phase. This likely introduced differences between groups and may have distorted the effect estimate.

[i] Downgraded one level for serious indirectness. The study reported a composite outcome (methicillin-resistant *Staphylococcus aureus* [MRSA] acquisitions, colonisations, or infections after 48 h) that did not exclusively assess MRSA colonisation.

[j] Downgraded three levels for extremely serious imprecision. The 95% CI of the absolute effect includes from moderate benefit to moderate harm (crosses more than three thresholds).

[k] Downgraded two levels for very serious risk of bias. High risk due to the randomisation process, deviations from the intended interventions, missing outcome data, and outcome measurement. Some concerns about selective reporting.

[l] Downgraded three levels for extremely serious imprecision. Neither the effect estimate nor its 95% CI was reported. The sample was small (70 patients analysed).

[m] Downgraded three levels for extremely serious imprecision. Neither the effect estimate nor its 95% CI was reported. The staff sample size was not reported, but it was probably small.

[n] Downgraded one level for serious risk of bias. High risk due to deviations from intended interventions.

[o] Not downgraded for imprecision. The 95% CI of the absolute effect was limited to values consistent with a trivial or no effect.

[p] The study did not plan to assess *C. difficile* colonisation. This outcome was added later with supplemental funding. As a result, *C. difficile* surveillance covered only a shorter period, whereas vancomycin-resistant Enterococci surveillance spanned the full study duration.

[q] Downgraded two levels for very serious imprecision. The 95% CI of the absolute effect includes from trivial effect to moderate harm. It crosses two thresholds.

1.66; 1 RCT [25]; ARD: − 3 ‰, 95% CI: − 57 to 77‰; very-low-certainty evidence). Wilson also reported colonisations by other micro-organisms, such as *C. difficile* [25], but these outcomes were ineligible because the hospital screened only for MRSA. We included colonisation outcomes only when a screening policy for the micro-organism was in place.

Adverse effects in patients and in staff

It is very uncertain whether increasing the frequency of high-touch surface disinfection affects safety as this was reported in only one study [21]. The authors stated that no patients reported adverse effects and that no staff reported any complaints. Conclusions are limited by the small sample size (patients: 70; staff: not reported) and short follow-up period (patients: mean: 4.9—6.8 days; staff: not reported).

c. No-touch disinfectants: UV light—emitting devices

Three RCTs (BETR trial [15], Lowering the Acquisition of Multidrug-Resistant Organisms with Pulsed-xenon (LAMP) trial [18], and the study by Rock *et al.* [22]) evaluated UV light—emitting devices, but only two [18,22] reported our review outcomes. The BETR trial [15] assessed four terminal room disinfection strategies (standard manual disinfection based on QAC or bleach for *C. difficile*, standard plus UV-C, bleach alone, and bleach plus UV-C) but did not report any eligible outcomes. The LAMP study [18] compared pulsed xenon UV with sham intervention for terminal decontamination in 15 units (10 wards and five ICUs). Rock [22] added UV-C light to routine and terminal decontamination in four cancer and one solid organ transplant inpatient units.

Comparison 6: Adding UV light to standard practice versus standard practice alone

Hospital-acquired colonisations (vancomycin-resistant enterococci)

Adding UV light to standard practice probably results in little to no difference in vancomycin-resistant enterococcus colonisations (IRR: 1.00, 95% CI: 0.79 to 1.25; 1 RCT [22]; ARaD: 0 cases per 1000 patient-days, 95% CI: − 4 to 5; moderate-certainty evidence).

Hospital-acquired colonisations (C. difficile)

The evidence is very uncertain regarding the effects of adding UV light to standard practice on *C. difficile* colonisations (IRR: 1.58, 95% CI: 0.97 to 2.58; 1 RCT [22]; ARaD: 6 cases per 1000 patient-days, 95% CI: 0 to 16; very low-certainty evidence).

Hospital-acquired infections

The evidence is very uncertain regarding the effect of adding pulsed xenon UV light to standard practice versus a sham intervention on HAIs (IRR: 1.10, 95% CI: 0.48 to 2.51; re-analysed due to unit-of-analysis error; 1 RCT [18]; ARaD: 2 cases more per 1000 patient-days, 95% CI: − 9 to 26; very-low-certainty evidence).

d. Antimicrobial surfaces

One RCT assessed replacing high-touch ICU surfaces with copper-coated materials [23]. Both arms also used routine and

[r] Corrected for unit-of-analysis error because the analysis did not account for the cluster design. We applied an approximate analysis by inflating the standard error with the design effect. The revised estimate (rate ratio: 1.10, 95% CI: 0.48 to 2.51) was similar to the original (rate ratio: 1.10, 95% CI: 0.94 to 1.29). The paper states that Poisson regression was used but does not clarify whether clustering was addressed. Given that the intervention and randomisation occurred at the unit level (15 units across two hospitals), failure to adjust for within-cluster correlation is likely. This is important because nearly half of HAI cases involved patient transfers between units; environmental interventions act at the cluster level; and not accounting for clustering can lead to overly narrow confidence intervals and misleading statistical precision.

[s] Downgraded one level for serious risk of bias. Some concerns with the randomisation process.

[t] We re-defined the outcome. The registry specified the objective as reducing HAIs, but the article did not report the frequency of HAIs directly. Table II reported 'HAI and/or colonization' and 'HAI only', which excluded patients with both outcomes. Following the approach described in the study by Harbarth 2013 (PMID: 23917919), we recalculated the outcome as 'patients with at least one HAI' to obtain a patient-level measure consistent with the trial objective.

[u] Downgraded two levels for very serious risk of bias. High risk in randomisation process and selective reporting. Some concerns with the outcome measurement.

[v] Downgraded two levels for very serious risk of bias. High risk in the randomisation process and missing outcome data (suggested by sensitivity analysis in pessimistic and optimistic scenarios). Some concerns with outcome measurement and selective reporting.

[w] Downgraded three levels for extremely serious imprecision. The 95% CI of the absolute effect scenario includes from large benefit to trivial effect (crosses three thresholds).

[x] Thresholds all-cause mortality ICU (absolute risk differences per 1000 patients): small (2‰), moderate (5‰), and large (10‰).

[y] Downgraded two levels for very serious risk of bias. High risk in randomisation process and some concerns with selective reporting.

[z] Downgraded two levels for very serious risk of bias. High risk in the randomisation process and missing outcome data. Some concerns with outcome measurement and selective reporting.

[aa] Downgraded three levels for extremely serious imprecision. It was only stated that the length of ICU stay did not differ between groups, with a median of 4 days in both ($P = 0.74$). A 95% CI for the difference of medians cannot be calculated from the available information.

terminal disinfection with QACs (or bleach for suspected or confirmed *C. difficile*) and *CaviCide*™ (a combination of alcohol and QAC) for spot cleaning. We found no RCTs evaluating other antimicrobial surfaces, such as zinc, silver, triclosan, bacteriophages, cationic nanoparticles, light-activated coatings, or surfaces with modified topographies or anti-adhesive properties.

Comparison 7: Copper-surfaces versus standard surfaces in the ICU

Hospital-acquired infections

The evidence is very uncertain regarding the effect on HAIs (RR: 0.64, 95% CI: 0.36 to 1.14; 1 RCT [23]; re-analysed by the reviewers; ARD: − 86 ‰, 95% CI: − 154 ‰ to 34‰; very-low-certainty evidence).

Bloodstream infections

The evidence is very uncertain regarding the effect on BSIs (RR: 0.30, 95% CI: 0.08 to 1.05; 1 RCT [23]; ARD: − 56 ‰, 95% CI: − 74 ‰ to 4‰; very-low-certainty evidence).

All-cause mortality

The evidence is very uncertain regarding the effect on all-cause mortality (RR: 0.91, 95% CI: 0.63 to 1.33; 1 RCT [23]; ARD: − 13 ‰, 95% CI: − 56 ‰ to 50‰; very-low-certainty evidence).

Length of hospital stay

One RCT [23] reported this outcome incompletely. It was only stated that ICU length of stay did not differ between groups, with a median of 4 days in both ($P = 0.74$). Thus, the effect of ICU copper surfaces on the length of hospital stay remains very uncertain.

e. Other aspects evaluated

One RCT [24], published in 1976, compared using phenolic disinfectant on operating room floors only after contaminated or septic procedures versus after all procedures; however, this study did not report any review outcomes.

Discussion

Principal results

We included 11 RCTs (eight CRXO-RCTs and three i-RCTs) with 70—21,395 adults of both sexes recruited between 2007 and 2017 in academic hospitals in high-income countries. Participants were mostly white, gender identity and socioeconomic status were unreported, and comorbidities were poorly described. Seven trials reported financial conflicts.

Studies evaluated manual agents (QACs, bleach, probiotics, IHP, and ultramicrofibre with copper), no-touch approaches (UV-C and pulsed xenon UV), or antimicrobial copper surfaces. Interventions were multi-component and applied during routine, terminal, or both routine and terminal decontamination. Intervention periods ranged from 7 days to 24 months; nine studies lasted ≥9 months, allowing effect evaluation beyond seasonality.

Despite the relevance of this topic and numerous interventions, few RCTs were conducted. None of them assessed detergents, steam, ozone, or non-copper antimicrobial surfaces. Only one study reported adverse effects, and none examined resistance to antibiotics or disinfectants. Most of the available evidence is based on non-randomised uncontrolled studies and focusses on surface contamination rather than HAIs.

Evidence on the effects of hospital surface decontamination on patient-centred outcomes is inconclusive because of few RCTs and their very-low-certainty evidence, mainly due to risk of bias and imprecision. These inconclusive findings should not be interpreted as evidence of no effect of decontamination or justify avoiding its use in hospitals. Given the routine bundled hospital infection prevention measures, such as hand hygiene and antimicrobial stewardship, HAI rates are typically low. This makes it difficult to isolate the specific impact of environmental decontamination from other measures. Although four ongoing RCTs exist, three assessing HAIs, further robust RCTs are still needed to evaluate conventional methods, such as cleaning without disinfectants, and emerging technologies and clarify their impact on patient-centred outcomes.

Strengths and limitations of the review

This review has strengths. First, we followed Cochrane/GRADE methods [11,12], including predefined thresholds for interpreting absolute effects. The broad review scope provides a comprehensive overview, and we focussed on RCTs, the most reliable design for estimating effects and isolating the contribution of decontamination within multi-component bundles, offering valuable insights for practice [32]. We prioritised patient-relevant outcomes (HAIs, colonisations, or adverse effects) and excluded surface contamination outcomes due to uncertain clinical relevance and lack of standard definitions [33]. We also excluded composite outcomes (e.g. combining several micro-organisms or mixing 'colonisation, infection, or both'), which assume equal importance among distinct events, mix biological pathways, and hinder interpretation [34]. Instead, we focussed on non-composite outcomes related to any HAI, which is biologically and clinically meaningful [31]. This approach explains why some trials did not contribute usable outcome data.

This review has limitations. Evidence was scarce and heterogeneous, including inconsistent outcome measurement, preventing meta-analyses. Most RCTs were underpowered for HAIs, producing wide CIs and very serious imprecision. RCTs are also limited for detecting rare adverse effects. Finally, several studies had financial conflicts of interest.

Comparison with prior work

Previous reviews consistently called for more research on environmental surface decontamination as the evidence presents consistent limitations [35—38]. First, bundled interventions make it difficult to isolate the effect of surface decontamination and the heterogeneity of interventions prevents meta-analyses. Second, studies often measure surface contamination rather than HAIs, and most evidence comes from laboratories rather than clinical settings. Third, few RCTs exist, and most studies have observational or on non-randomised uncontrolled designs.

Our review identified all relevant RCTs from prior reviews and reached similar conclusions. We excluded some of their

RCTs because of ineligible interventions (e.g. infection control bundles or copper-treated textiles), outcomes (focussed only on microbial surface burden), or designs (non-randomised studies). Notably, most previous reviews lacked robust methods, often omitting risk-of-bias or certainty assessments. For example, only one used GRADE [39]. We support previous calls for a core outcome set for decontamination trials focussed on clinical outcomes rather than microbial surface burden [38].

Our review aligns with that of Alsaggaf [40], which reported that most decontamination studies were uncontrolled. We also agree that although decontamination can reduce microbial surface burden, its impact on HAIs in complex healthcare settings with multiple transmission pathways remains unclear [9]. However, we disagree with Schmidt [41], who states that GRADE is unsuitable for evaluating infection control trials: This method is valuable for guiding evidence-based decisions in infection control, including emergencies such as the COVID pandemic [42].

Implications for practice and research

Evidence for most intervention—outcome pairs is limited, and it remains uncertain whether cleaning or disinfection works or whether the comparative effects between interventions differ. The impact of decontamination frequency, timing (routine or terminal decontamination), targeted areas (e.g. high-touch surfaces or areas with infected or colonised patient), or specific equipment (e.g. microfiber mops) is also uncertain. These inconclusive findings do not imply no effect but highlight the need for better evidence to guide decisions.

When RCTs provide only low- or very-low-certainty evidence, well-designed non-randomised studies, including observational designs, can complement the evidence base [43]. Including such studies can increase certainty, particularly when they address gaps in RCTs (e.g. rarely evaluated interventions or outcomes, short follow-ups, or non-diverse populations). Although not the focus of this review, which included only RCTs, there are good examples of non-randomised studies that can support decision-making [5,44].

Given the potential benefit of decontamination, new RCTs of decontamination interventions are needed to inform protocols and reduce practice variability. They should be prospectively registered, multi-centre, and cluster-RCTs adequately powered for patient-relevant outcomes. Adverse outcomes should be considered as well, and composite outcomes should be avoided. Larger sample sizes and numerous clusters are needed to assess infection prevention outcomes in cluster-RCTs [45]. Publicly funded studies in low-resource and non-Western settings should be encouraged to generate evidence regarding applicable interventions, including cleaning without disinfectants, across diverse settings. Finally, the development of reporting guidelines and a core outcome set for decontamination trials is needed. Universally accepted microbiological standards for surfaces would also support the evaluation and offer a concrete benchmark for modelling clinical infection risk [46].

Initiating hospital decontamination RCTs is challenging. Staff must change visible routines, making blinding unrealistic, and ward-level randomisation is logistically complex. Funding for basic cleaning research is limited unless linked to new technologies, leaving routine cleaning understudied. Improving evidence requires investment in pragmatic trial designs suited to hospital workflows and local contexts [47]. However, there are some viable alternatives to present a more optimistic view. First, infection prevention & control professionals recognise the difficulties with RCTs and support detailed epidemiological studies, especially if conforming to the Outbreak Reports and Intervention studies Of Nosocomial infection (ORION) statement [48]. Agencies responsible for reviews and meta-analyses should be aware of these guidelines. Second, genomic investigations are becoming ever more prevalent and affordable, and these can identify an evidence trail between environmental reservoirs and patients. Such molecular fingerprinting not only provides compelling evidence for HAI origins but also will permit assessment of cleaning interventions subject to systematic screening. Third, there remains the possibility of designing cleaning studies to examine non-superiority between one practice and another in order to compare costs. For example, take two similar hospitals with similar HAI rates: If one hospital uses expensive disinfectants and/or automated decontamination devices and another relies on detergent with occasional bleach, then the latter practice argues for greater economy and less environmental impact, so there are opportunities to demonstrate the impact of cleaning and decontamination outside the classical RCT. We hope that such studies will take place in future years.

Conclusion

Evidence from RCTs assessing the impact of hospital surface decontamination on patient outcomes remains inconclusive, but these findings should not be interpreted as evidence of no effect. Given the burden of HAIs, powered, non-industry-funded, multi-centre cluster-RCTs of cleaning and disinfection interventions are urgently needed, especially in low-resource settings, to detect meaningful differences in patient-relevant outcomes, including adverse events. Developing reporting guidelines and a core outcome set, including universally accepted microbiological standards for surfaces, would further standardise future trials and enhance their clinical relevance.

CRediT authorship contribution statement

J. Lopez-Alcalde: Writing — review & editing, Writing — original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Mateos-Mazón:** Writing — review & editing, Validation, Data curation. **L. Oliveira Conterno:** Writing — review & editing, Validation, Data curation. **S.J. Dancer:** Writing — review & editing, Validation, Data curation, Conceptualization. **E.C. Stallings:** Writing — review & editing, Methodology, Data curation. **G. Villanueva:** Writing — review & editing, Validation, Methodology, Data curation. **A.E. Gonzalez-Velez:** Writing — review & editing, Validation, Data curation. **S. Cabir Nunes:** Writing — review & editing, Validation, Data curation. **E. Jiménez-Tejero:** Writing — review & editing, Methodology, Data curation. **I. Solà:** Writing — review & editing, Validation, Methodology, Data curation, Conceptualization. **J. Zamora:** Writing — review & editing, Supervision, Methodology, Conceptualization. **X. Bonfill Cosp:** Writing — review & editing, Validation, Resources, Project administration, Methodology, Conceptualization.

Availability of data and materials

All the data generated during this study are included in the manuscript. The template of the data collection form and the detailed risk of bias assessments are available upon request.

Ethics statement

Ethics approval was not required as the research did not include human participants, human data or tissue, or animals.

Provenance and peer review

Not commissioned; externally peer reviewed.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT and Grammarly in order to improve the readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.infpip.2026.100514.

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