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**Literature Review of
Surface Sample Collection Methods**

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14. ABSTRACT (LESS THAN 200 WORDS): The U.S. Army Combat Capabilities Development Command Chemical Biological Center reviewed surface sample collection methods to identify which methods effectively detected biological threat agents dispersed via aerosol at relatively low concentrations. The review was conducted by analyzing various studies evaluating the collection methods of vacuuming, swabbing, and wiping biological threat agents from various surfaces. More than 30 reports were analyzed, but only 21 had sufficient data to report. Vacuum sampling was most efficient for collection of biological agents from large, porous surface areas. Swab sampling was most appropriate for sampling small areas with high agent concentrations; moist swabs were preferable to dry swabs. Wipe sampling often resulted in higher recovery efficiencies and lower limits of detection than vacuum or swab sampling and may be most practical for sampling larger areas; premoistened wipes were often preferable to dry. It was concluded that all sample collection methods were effective for detecting different concentrations of various biological agents dispersed via aerosol; however, environmental and situational factors and surface type differences will determine the best method for sample collection. Additionally, gaps in the studies reviewed made it difficult to make direct comparisons between sampling methods and materials.					
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PREFACE

The work described in this report was authorized under contract no. GSQ0816BP0057. The work was started in October 2018 and completed in October 2019. At the time this work was performed, the U.S. Army Combat Capabilities Development Command Chemical Biological Center (DEVCOM CBC; Aberdeen Proving Ground, MD) was known as the U.S. Army Edgewood Chemical Biological Center (ECBC).

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LITERATURE REVIEW OF SURFACE SAMPLE COLLECTION METHODS

1. INTRODUCTION

The U.S. Army Combat Capabilities Development Command Chemical Biological Center (Aberdeen Proving Ground, MD) performed a literature review of surface sample collection methods. The objective of the review was to determine which surface sample collection methods could be most effective in the detection of biological threat agents dispersed via aerosol at relatively low concentrations. Secondary objectives were to execute a market survey of surface sampling methods and kits; identify minimum surface sampling size requirements to reach detection limits for common instruments; and compare efficiencies, pros and cons, and benefits and limitations for surface sampling versus direct aerosol sampling equipment at both high and low flow rates.

1.1 Scope

The literature review was restricted to include methods and kits with published or stated recovery efficiencies and those that were compatible with common biological detection systems.

1.2 Literature Review Methodology

Thirty-six initial studies were discovered and identified through an initial open-source search, which included publication databases (i.e., PubMed), the Defense Technical Information Center (<https://discover.dtic.mil/>), and other government agencies' protocols, such as those from the Centers for Disease Control and Prevention (CDC; Atlanta, GA), U.S. Environmental Protection Agency (EPA; Washington, DC), and National Institute for Standards and Technology (Gaithersburg, MD). Of the 36 studies reviewed, 15 were excluded, and 21 were included in the final assessment. Excluded studies are listed in the bibliography. Multiple criteria were used to determine which studies were used in the final review. The primary criteria considered were the use of aerosol deposition, published or stated collection efficiencies, and applicability.

Three main sampling methods were used throughout all studies: vacuum, swab, and wipe or sponge sampling. For each sampling method, various materials were used to sample different surface types and sizes under differing environmental conditions for the presence of a variety of biological threat agents. Throughout this literature review, each sampling method is expanded on, and relevant data sets from completed studies are analyzed and compared.

The appendix includes pricing information on kits or materials used for the sample collection methods in the studies reviewed. This pricing information is for sample collection materials only and does not include the laboratory equipment required to use those specific materials.

2. SAMPLING METHODS

Various sampling methods are currently used and recommended for sampling of biological agents. One objective of this literature review was to summarize available data for current and established sampling methods. The data elements of most interest included the following:

- aerosol deposition;
- stated recovery efficiencies;
- applicability to current program;
- compatibility with electrochemiluminescence (ECL) or polymerase chain reaction (PCR);
- surface type sampled;
- range of aerosol particle sizes;
- range of aerosol settling rates;
- cost of method; and
- detection of bacteria, toxin, or virus.

Table 1 summarizes the number of studies reviewed per sampling method. Some studies included more than one sampling method.

Table 1. Sampling Method and Quantity of Sources

Sampling Method	No. of Sources
Vacuum	5
Swab	9
Wipe or sponge	11

Note that all 21 studies reviewed for final assessment are not represented in the data, as some were better suited for comparing methods and drawing conclusions than for data analysis.

2.1 Vacuum Sampling

Five vacuum sampling studies were included in this review; details of each study are shown in Table 2. The 2007 study by Brown and coworkers (1) was completed using a vacuum filter sock to recover *Bacillus atrophaeus* spores from porous and nonporous surfaces. There were no statistical differences between recovery efficiencies across the various surface types. The authors concluded that negative vacuum filter sock samples do not ensure that organisms are absent from the surfaces sampled and may not ensure the absence of the potential for exposure.

The 2013 study by Calfee and coworkers (2) compared the use of four different sampling devices (vacuum socks, 37 mm mixed cellulose ester [MCE] filter cassettes, 37 mm polytetrafluoroethylene filter cassettes, and 3M forensic filters [3M Company; Saint Paul, MN])

in the recovery of a *Bacillus anthracis* surrogate. The vacuum sock and the 37 mm MCE had significantly higher recovery rates when compared to the other methods tested; however, recovery rates were still lower than those from a previously completed study (3) that used the wipe-based method.

The 2011 study by Einfeld and coworkers (4) included a review of both vacuum and wipe sampling methods to recover *B. atrophaeus* spores from a variety of clean and dirty surface types under differing relative humidities. For vacuum sampling, there were no significant differences between recovery efficiencies from concrete compared to marble, and results were statistically similar across various humidity points, surface types, and clean versus dirty surfaces. Results showed that recovery efficiencies from the vacuum method were considerably lower than those from the wipe method.

The 2009 study by Estill and coworkers (5) was performed to help validate surface sampling techniques for biological agents at low surface loadings. *B. anthracis* spores were aerosolized at low surface loadings onto steel and carpet coupons. The vacuum filter sock was found to be able to detect anthrax concentrations as low as 44 colony forming units (cfu)/100 cm² on stainless steel coupons, whereas the wipe method was found to detect concentrations as low as 15 cfu/100 cm². On carpeting, the vacuum filter sock was found to be able to detect concentrations as low as 28 cfu/100 cm², whereas the wipe method was able to detect concentrations as low as 9.2 cfu/100 cm². It was demonstrated that the wipe sampling method had lower limits of detection than the vacuum for both stainless steel and carpet surface types.

In the 2008 study by Frawley and coworkers (6), researchers used dry trace evidence collection filters (TECFs) to recover *B. anthracis* spores and ricin from porous and nonporous surfaces. It was found that use of TECFs resulted in poor recovery efficiencies for both *B. anthracis* and ricin on all surfaces tested.

In summary, these studies generally indicate that vacuum sampling as a surface sampling method can be effective for the detection of some biological threat agents dispersed via aerosol at relatively low concentrations. However, to optimize recovery efficiency, it is often desirable to opt for swab or wipe methods instead. The CDC concluded that a 37 mm cassette is more efficient than a vacuum sock for using vacuum sampling, and the cassette also poses less risk of exposure to laboratory technicians (7).

Table 2. Collection of Select Vacuum Sampling Results

Source	Surface Type	Sample Size Area (cm ²)	Filter Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
1	Stainless steel	100	Vacuum sock	28.9	Yes, fluidized bed aerosol generator	24 h
	Painted wallboard			24.8		
	Industrial carpet			28.2		
	Concrete			18.9		
2	Carpet	2787	Vacuum sock	15.2 – fast 25.1 – slow	Yes, metered dose inhaler	18 h
	Concrete			11.7 – fast 10.2 – slow		
	Upholstery			9.1 – fast 4.2 – slow		
4	Concrete	81	Vacuum sock	High humidity: 19.7 – dirty surface 16.5 – clean surface	Yes, fluidized bed aerosol generator	24 h
	Marble	100		Mid humidity: 10.0 – dirty surface 11.9 – clean surface		
		High humidity: 17.0 – dirty surface 12.1 – clean surface				
5	Stainless steel	929	Vacuum sock	5.5 – low loading 4.7 – medium loading 3.7 – high loading	Yes, aerosol generation system	N/A
	Carpet			6.3 – low loading 3.7 – medium loading 4.7 – high loading		
6	Plastic	1	TECF	1.0 – <i>B. anthracis</i> 0.5 - ricin	No	N/A
	Wood			0.1 – <i>B. anthracis</i> 0.1 – ricin		
	Cotton cloth			0.7 – <i>B. anthracis</i> 0.9 – ricin		

N/A, not applicable.

2.2 Swab Sampling

Nine swab sampling studies were included in this review and are shown in Table 3. In another 2007 study (8), Brown and coworkers evaluated the CDC-recommended swab surface sample collection method for recovery of *B. atrophaeus* spores from nonporous surfaces. Recovery efficiencies were greater for both surfaces tested when surface loading was high. Researchers concluded that the swab sample collection method may be most appropriate for sampling small areas (10–25 cm²) with high agent concentration. Subsequently, samples collected that yielded positive results would indicate high surface concentrations and may imply

potential for exposure; however, negative swab samples would not ensure that organisms are absent from the surface samples and may not ensure the absence of the potential for exposure.

In the 2007 study by Buttner, Cruz, Stetzenbach, and Cronin (9), the researchers aimed to evaluate macrofoam swab surface sampling protocols for use with culture and quantitative polymerase chain reaction (QPCR) for detection of *Erwinia herbicola* on seven different surfaces. The swab showed the greatest recovery efficiency (52.2%) with QPCR on the glass surface material and the lowest recovery efficiency (0.8%) on finished concrete. QPCR was able to demonstrate that DNA was present on all surface materials tested, whereas culture analysis was ineffective. When compared with a Speci-Sponge (Nasco Healthcare; Fort Atkinson, WI), the macrofoam swab collection method was more efficient.

In a 2001 study (10), Buttner, Cruz-Perez, and Stetzenbach evaluated a swab kit and a sponge swipe sampling method for detection of *Bacillus subtilis* endospores on various flooring materials when in the presence of high and low levels of *Penicillium chrysogenum* as a background contaminant. Both swab and sponge were found to be effective for detection and quantitation of spores, and no significant differences were identified between sampling methods for any flooring material tested. Therefore, selection of a sampling method may depend on the field situation: a sponge swipe may be most practical for large sampling areas, whereas a swab may be most efficient on smooth, vinyl surfaces. Although both QPCR and culture analysis were used, QPCR showed overall greater sensitivity than culture analysis, and the presence of background *P. chrysogenum* did not have an inhibitory effect on QPCR. The 2001 and 2007 reports by Buttner and colleagues demonstrate the capabilities of QPCR to enhance detection and enumeration of biocontaminants on a variety of surface materials.

The 2009 study by Edmonds and coworkers (11) was performed to determine whether liquid application of *B. atrophaeus* altered the sampling data in comparison to aerosol deposition. Tests were performed with four unique swabbing materials applied to four different surfaces. The results showed that recovery of liquid deposited spores does vary significantly from recovery of aerosol deposited spores; whether the recoveries were elevated or decreased depended on the surface material being tested. No single swab material outperformed any of the other three.

A 2012 study by Edmonds, Collett, Brown, and Mangaya (12) was performed to determine whether liquid application of ricin altered the sampling data in comparison to aerosol deposition. For all surfaces and all swab types, recovery efficiencies were higher for samples deposited via liquid. In many cases, the recovery efficiency was below a detectable limit for toxins deposited via aerosol. This study demonstrated the need for more research on sampling environments where toxin material may be released.

The 2009 study by Estill and coworkers (5) was performed to help validate surface sampling techniques for biological agents at low surface loadings. *B. anthracis* spores were aerosolized at low surface loadings onto steel and carpet coupons. For swab sample collection, there was a higher recovery efficiency at medium deposition for both steel and carpet surfaces; however, the wipe method showed overall better recovery. It was also demonstrated that the wipe sampling method had a lower limit of detection for both stainless steel

(15 cfu/100 cm²) and carpet (9.2 cfu/100 cm²) than the swab (190 and 40 cfu/100 cm² for stainless steel and carpet, respectively).

In the 2008 study by Frawley and coworkers (6), two substudies aimed to establish the best procedures for sampling surfaces likely to be contaminated after the release of *B. anthracis* or ricin. In the first study, dry and moist polyester swabs were used to recover *B. anthracis* spores and ricin from plastic, wood, and a cotton cloth. For both agents, dry swabs had universally poor recovery efficiencies, and moist swabs were superior in performance. Results from this study show it is possible to demonstrate the presence of ricin on everyday surfaces in the event of a release. In the second study, contact plates were compared with wet cotton swabs for recovery of *B. anthracis* spores from various surfaces. Contact plates performed better than swabs by a wide margin for flat nonporous surfaces.

A 1979 study by Kirschner and Puleo (13) endeavored to address inherent inadequacies in a previously accepted cotton swab-rinse technique by evaluating an alternative wipe-rinse technique for the bioassay of large stainless steel areas. The recovery efficiency of cotton swabs was compared with the recovery efficiencies of two wipe materials, polyester-bonded cloth (PBC) and cellulose cloth. PBC showed a superior recovery efficiency (90.4%) compared to cellulose (72%) and cotton swabs (75.2%).

In a 2004 study by Rose and coworkers (14), four swab materials (cotton, macrofoam, polyester, and rayon) were evaluated for their efficiency in recovery of *B. anthracis* that was spread directly onto the surface material. Results indicated that premoistened swabs of all types were more efficient at recovering spores than dry swabs. Three methods of processing for the removal of spores from the swabs (vortexing, sonication, and minimal agitation) were also tested. Premoistened macrofoam and cotton swabs that were vortexed during processing had the highest recovery efficiencies, whereas polyester and rayon swabs were less efficient. Swabs processed using sonication or minimal agitation as a method of extraction had no significant differences in recovery efficiency.

In summary, these studies indicate that swab sampling as a surface sampling method can be effective in the detection of some biological threat agents dispersed via aerosol at relatively low concentrations and often results in higher recovery efficiencies than vacuum sampling. The swab sample collection method may be most appropriate for sampling small areas (10–25 cm²) with high agent concentrations, and moist swabs are preferable to dry; however, which swab type optimizes recovery efficiency depends on the surface material being tested. The CDC recommends a macrofoam swab as the preferred swab material for recovering *B. anthracis* from smooth nonporous surfaces (7). QPCR has been shown to enhance detection and enumeration of biocontaminants on a variety of surface materials. In many cases, recovery efficiencies of toxins deposited via aerosol were below detectable limits, revealing the need for further research on sampling environments where toxin material may be deposited in this manner.

Table 3. Collection of Select Swab Sampling Data

Source	Surface Type	Sample Size Area (cm ²)	Swab Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
8	Stainless steel	25	Sterile rayon	42.9 – high load 39.5 – low load	Yes, fluidized bed aerosol generator	24 h
	Painted wallboard			45.6 – high load 35.5 – low load		
9	Metal	317	Macrofoam	<0.005 – culture 39.5 – QPCR	Yes, Collison nebulizer	Overnight
	Glass			0.005 – culture 52.2 – QPCR		
	Nylon cushion			<0.005 – culture 3.9 – QPCR		
	Vinyl tile			<0.005 – culture 41.1 – QPCR		
	Wood laminate			<0.005 – culture 28.6 – QPCR		
	Plastic seat			<0.005 – culture 31.2 – QPCR		
	Finished concrete			<0.005 – culture 0.8 - QPCR		
10	Vinyl tile	32.49	Swab kit	Culture 30.0 – high Bkg 7.7 – low Bkg	Yes, dry aerosol generator	N/A
				PCR 25.1 – high load 1.4 – low load		
	Commercial carpet			Culture 26.0 – high Bkg 5.7 – low Bkg		
				PCR 27.2 – high Bkg 0.1 – low Bkg		
	Residential carpet			Culture 7.0 – high Bkg 7.1 – low Bkg		
				PCR 12.5 – high Bkg 9.2 – low bkg		
	Soiled residential carpet			Culture 14.9 – high Bkg 13.9 – low Bkg		
				PCR 19.0 – high Bkg 16.0 – low Bkg		

(Continued)

Table 3. Collection of Select Swab Sampling Data (Continued)

Source	Surface Type	Sample Size Area (cm ²)	Swab Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
11	Glass	10	Cotton	88.7 – aerosol 62.4 – liquid	Yes, nebulizer	Overnight
			Dacron	64.9 – aerosol 82.1 – liquid		
			Rayon	65.2 – aerosol 87.5 – liquid		
			Macrofoam	61.2 – aerosol 89.1 – liquid		
	CARC-painted steel		Cotton	51.9 – aerosol 47.0 – liquid		
			Dacron	57.6 – aerosol 42.5 – liquid		
			Rayon	53.1 – aerosol 43.6 – liquid		
			Macrofoam	51.5 – aerosol 55.7 – liquid		
	Polycarbonate		Cotton	65.1 – aerosol 74.9 – liquid		
			Dacron	71.9 – aerosol 83.4 – liquid		
			Rayon	68.9 – aerosol 75.4 – liquid		
			Macrofoam	75.5 – aerosol 88.3 – liquid		
	Vinyl tile		Cotton	60.3 – aerosol 49.0 – liquid		
			Dacron	68.7 – aerosol 62.2 – liquid		
			Rayon	60.2 – aerosol 58.3 – liquid		
			Macrofoam	67.0 – aerosol 72.0 – liquid		
12	Glass	10	Cotton	7.2 – aerosol 56.7 – liquid	Yes, nebulizer	Overnight
			Dacron	12.9 – aerosol 69.5 – liquid		
			Rayon	BDL – aerosol 54.6 – liquid		
			Macrofoam	9.7 – aerosol 60.5 – liquid		
	CARC-painted steel		Cotton	BDL – aerosol 49.6 – liquid		
			Dacron	25.2 – aerosol 76.0 – liquid		
			Rayon	BDL – aerosol 60.1 – liquid		
			Macrofoam	BDL – aerosol 65.3 – liquid		

(Continued)

Table 3. Collection of Select Swab Sampling Data (Continued)

Source	Surface Type	Sample Size Area (cm ²)	Swab Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
12	Polycarbonate	10	Cotton	13.1 – aerosol 58.7 – liquid	Yes, nebulizer	Overnight
			Dacron	38.5 – aerosol 72.8 – liquid		
			Rayon	7.5 – aerosol 64.4 – liquid		
			Macrofoam	12.2 – aerosol 65.4 – liquid		
	Vinyl tile		Cotton	BDL – aerosol 47.3 – liquid		
			Dacron	18.0 – aerosol 70.5 – liquid		
			Rayon	BDL – aerosol 64.4 – liquid		
			Macrofoam	BDL – aerosol 58.3 – liquid		
5	Stainless steel	103	Prewet foam critical swab	3.4 – low load 6.5 – medium load 5.0 – high load	Yes, aerosol generation system	10 h
	Carpet			12.0 – low load 14.0 – medium load 12.0 – high load		
6 Study 1	Plastic	1	Polyester swab	Dry 2.3 – <i>B. anthracis</i> 1.0 – ricin	No	N/A
	Wood			Moist 5.5 – <i>B. anthracis</i> 2.5 – ricin		
				Dry 0.3 – <i>B. anthracis</i> 0.3 – ricin		
	Cotton cloth			Moist 2.5 – <i>B. anthracis</i> 2.1 – ricin		
				Dry 0.6 – <i>B. anthracis</i> 1.4 – ricin		
	Moist 2.0 – <i>B. anthracis</i> 1.1 – ricin					
6 Study 2	Plastic	N/A	Prewet cotton swab vs contact plates	34.0 – contact 8.0 – swab	No	N/A
	Glass			42.0 – contact 15.0 – swab		
	Desktop Formica			28.0 – contact 15.0 – swab		
	Metal			54.0 – contact 14.0 – swab		

(Continued)

Table 3. Collection of Select Swab Sampling Data (Continued)

Source	Surface Type	Sample Size Area (cm ²)	Swab Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
6 Study 2	Carpet	N/A	Prewet cotton swab vs contact plates	5.0 – contact 2.0 – swab	No	N/A
	Brick			6.0 – contact 2.0 – swab		
	Synthetic cloth			3.0 – contact 0.0 – swab		
13	Stainless steel table with Teflon ribbons	130	Cotton swabs	75.2	Yes, 1 week exposure to intramural environment	N/A
14	Stainless steel	10.16	Cotton	5.1 – dry 20.0 – wet	No	N/A
			Macrofoam	8.4 – dry 22.5 – wet		
			Polyester	1.2 – dry 7.7 – wet		
			Rayon	3.0 – dry 7.0 – wet		

BDL, below detectable limit; Bkg, background; CARC, chemical agent resistant coating.

2.3 Wipe Sampling

A total of 11 wipe sampling studies were included in this review and are shown in Table 4. In 2007, Brown and coworkers (3) tested a polyester-rayon wipe for efficiency in recovering *B. atrophaeus* spores from stainless steel and painted wallboard. The mean recovery efficiency from stainless steel (34.6%) was significantly higher than that from painted wallboard (28.5%). Limits of detection were determined to be 90 cfu/unit of stainless steel and 105 cfu/unit of painted wallboard.

In another report by Buttner and coworkers (15), researchers evaluated the biological sampling kit (BiSKit; QuickSilver Analytics; Abingdon, MD) for recovering *B. atrophaeus* spores from a large sampling area. When compared with a cotton-based swab and a foam-based swab sample processing kit, the BiSKit collected significantly more spores per sample regardless of test material (wood laminate or metal) or assay (culture or QPCR). More spores were detected on BiSKit samples taken from metal compared with samples taken from wood laminate. All three methods resulted in positive handheld assay results, and BiSKit gave the strongest signal. The BiSKit demonstrated higher recovery efficiencies when used dry versus wet; however, the difference was not significant.

In the 2007 study by Buttner, Cruz, Stetzenbach, and Cronin (9), researchers evaluated Speci-Sponge surface sampling protocols for use with culture and QPCR for detection of *E. herbicola* on seven different surfaces. The sponge showed the greatest recovery efficiency (47.3%) with QPCR on the glass surface material and the lowest recovery efficiency (0.7%) on finished concrete. QPCR was able to demonstrate that DNA was present on all surface materials

tested, whereas culture analysis was ineffective. When compared with the macrofoam swab, the sponge collection method was less efficient; however, the detection sensitivities were similar. The larger surface area sampled by the sponge (930 cm² compared with 317 cm²) resulted in a comparable concentration of *E. herbicola* in samples for both swab and sponge.

In the earlier 2001 study by Buttner and coworkers (10), researchers evaluated a swab kit and a sponge swipe sampling method for detection of *B. subtilis* endospores on various flooring materials when in the presence of high and low levels of *P. chrysogenum* background contamination. Both swab and sponge were found to be effective for detection and quantitation of spores, and no significant differences were observed between sampling methods for any flooring material tested. Therefore, selection of a sampling method may depend on the field situation: a sponge swipe may be most practical for large sampling areas, whereas a swab is most efficient on smooth, vinyl surfaces. Although both QPCR and culture analysis were used, QPCR showed overall greater sensitivity than culture analysis, and the presence of background *P. chrysogenum* did not have an inhibitory effect on QPCR. The results of the 2001 and 2007 studies by Buttner and colleagues demonstrate the capabilities of QPCR to enhance detection and enumeration of biocontaminants on a variety of surface materials.

The 2011 study by Einfeld and coworkers (4) included a review of both vacuum and wipe sampling methods to recover *B. atrophaeus* spores from a variety of clean and dirty surface types under differing relative humidities. For wipe sampling, higher recovery efficiencies were observed from dirty (grime-covered) than from clean surfaces; however, the differences were not significant due to high recovery variability. Results showed that the wipe method resulted in considerably higher recovery efficiencies than the vacuum method.

The 2009 study by Estill and coworkers (5) was performed to help validate surface sampling techniques for biological agents at low surface loadings. *B. anthracis* spores were aerosolized at low surface loadings onto steel and carpet coupons. For wipe sample collection, recovery efficiency was higher at low deposition for both steel and carpet surfaces, and the wipe outperformed both the vacuum and swab methods. It was also demonstrated that the wipe sampling method had a lower limit of detection for both stainless steel (15 cfu/100 cm²) and carpet (9.2 cfu/100 cm²) than the swab (190 and 40 cfu/100 cm², respectively).

In the 2008 study by Frawley and coworkers (6), researchers tested a sample collection and recovery device (SCRD) and both dry and moist gauze wipes to recover *B. anthracis* spores and ricin from plastic, wood, and cotton cloth. For both agents, moist wipes were superior in performance to dry wipes. The premoistened gauze wipes had higher recovery efficiencies than the SCRd for *B. anthracis*; however, both showed similar recovery efficiencies for ricin. Generally, wipes were found to be more effective than swabs or vacuum sampling.

A study from 1979 by Kirschner and Puleo (13) evaluated a wipe-rinse technique for the bioassay of large stainless steel areas to address inherent inadequacies in a previously accepted cotton swab-rinse technique. Recovery efficiencies of PBC and cellulose cloth were compared with the recovery efficiency of cotton swabs. PBC showed a superior recovery efficiency (90.4%) compared with cellulose (72%) and cotton swabs (75.2%).

In 2012, Krauter and coworkers (16) aimed to test the sponge wipe sampling method at low contaminant concentrations and quantify associated false-negative rates. Researchers tested 10 different concentrations of *B. atrophaeus* spores on a variety of surfaces. Ceramic tile (48.9%) and stainless steel (48.1%) had higher mean recovery efficiency values than faux leather, vinyl tile, painted wood, or plastic. Smoother surfaces resulted in higher mean recovery efficiencies and lower false-negative rates. This study found that recovery efficiencies were not influenced by low spore concentration.

In 2010, Lewandowski and coworkers (17) assessed the efficiency of a foam spatula wipe in recovering aerosolized *B. atrophaeus* spores from glass. The recovery efficiency of a wet surface-collector (15.2%) was compared with that of the foam spatula (9.9%). This result indicated that using a foam spatula wipe permits reliable sampling of spores from a bioaerosol-exposed surface; however, the authors determined that further work is needed to improve the analysis of the foam extracts to decrease the limit of detection. An additional study was performed during this effort that compared the number of colony-forming units per unit area collected by a macrofoam sponge wipe and a polyester swab. The macrofoam sponge wipe was found superior to the polyester swab; however, data are not included in the swab section or wipe data table of this review because recovery efficiencies were not reported.

A 2011 study by Probst and coworkers (18) was completed to determine the most efficient wipe sampling collection method for recovery of spores of various *Bacillus* species from rough surfaces. The experiment compared a novel wipe-rinse technique (foam spatula) to the European Space Agency standard wipe assay (polyester wipe) in sampling of four spacecraft-related surfaces. The average recovery efficiency for the foam spatula protocol was 41.1%, approximately triple the average recovery efficiency for the standard wipe assay (13.9%). The foam spatula protocol demonstrated a strong advantage in spore load detection on spacecraft-related surfaces.

In summary, these studies indicate that wipe sampling as a surface sampling method can be effective in the detection of some biological threat agents dispersed via aerosol at relatively low concentrations and often results in higher recovery efficiencies and lower limits of detection than vacuum or swab sampling. The wipe sample collection method may be most practical for sampling larger areas (>25 cm²), premoistened wipes are often preferable to dry, and determining which wipe material to use to optimize recovery efficiency depends on the surface material being tested. The CDC recommends a cellulose sponge wipe as the preferred wipe material for recovering *B. anthracis* from smooth nonporous surfaces (7). Additionally, it has been determined that whether the entire surface of a sponge is used or just one side, there is no overall impact on the recovery efficiency (19). The only study that attempted to recover toxins showed no difference in performance between the two tested wipe methods, revealing the need for further research on toxin sampling.

Table 4. Collection of Select Wipe Sampling Data

Source	Surface Type	Sample Size Area (cm ²)	Wipe Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
3	Stainless steel	25	Sterile polyester-rayon blend gauze wipe	34.6	Yes, fluidized bed aerosol generator	24 h
	Painted wallboard			28.5		
15	Metal	100	BiSKit	18.4 – dry 11.3 – wet	No	N/A
9	Metal	930	Speci-sponge	<0.005 – culture 44.8 – QPCR	Yes, Collison nebulizer	Overnight
	Glass			0.006 – culture 47.3 – QPCR		
	Nylon cushion			<0.005 – culture 11.3 – QPCR		
	Vinyl tile			<0.005 – culture 25.8 – QPCR		
	Wood laminate			<0.005 – culture 11.4 – QPCR		
	Plastic seat			<0.005 – culture 18.1 – QPCR		
	Finished concrete			<0.005 – culture 0.7 – QPCR		
10	Vinyl tile	32.49	Sponge swipe	Culture 39.2 – high Bkg 10.2 – low Bkg	Yes, dry aerosol generator	N/A
				PCR 12.8 – high Bkg 7.3 – low Bkg		
	Commercial carpet			Culture 11.1 – high Bkg 8.3 – low Bkg		
				PCR 9.9 – high Bkg 3.8 – low Bkg		
	Residential carpet			Culture 0.2 – high Bkg 10.8 – low Bkg		
				PCR 3.3 – high Bkg 59.5 – low Bkg		
	Soiled residential carpet			Culture 12.7 – high Bkg 13.4 – low Bkg		
				PCR 8.6 – high Bkg 9.0 – low Bkg		

(Continued)

Table 4. Collection of Select Wipe Sampling Data (Continued)

Source	Surface Type	Sample Size Area (cm ²)	Wipe Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
4	Stainless steel	100	Versalon sponge (rayon-polyester)	Low humidity 96.8 – dirty 79.7 – clean	Yes, Fluidized bed aerosol generator	24 h
				High humidity 19.8 – dirty 18.0 – clean		
	High humidity 54.7 – dirty 33.3 – clean					
	Low humidity 59.5 – dirty 48.2 – clean					
	High humidity 68.5 – dirty 43.6 – clean					
Glass	Marble	929	Versalon sponge	31.0 – low load 22.0 – medium load 18.0 – high load	Yes, aerosol generation system	N/A
				120.0 – low load 21.0 – medium load 23.0 – high load		
6	Plastic	1	Gauze wipe	Dry 0.9 – <i>B. anthracis</i> 0.6 – ricin	No	N/A
				Moist 6.6 – <i>B. anthracis</i> 2.5 – ricin		
			SCRD	4.1 – <i>B. anthracis</i> 2.2 – ricin		
			Gauze wipe	Dry 0.2 – <i>B. anthracis</i> 0.2 – ricin		
	Moist 6.0 – <i>B. anthracis</i> 1.4 – ricin					
	SCRD		3.6 – <i>B. anthracis</i> 1.5 – ricin			
	Wood		Gauze wipe	Dry 0.9 – <i>B. anthracis</i> 0.6 – ricin		
				Moist 4.0 – <i>B. anthracis</i> 2.0 – ricin		
			SCRD	1.7 – <i>B. anthracis</i> 1.5 – ricin		
			Cotton cloth	PBC		
Cellulose cloth	72.0					

(Continued)

Table 4. Collection of Select Wipe Sampling Data (Continued)

Source	Surface Type	Sample Size Area (cm ²)	Wipe Type	Recovery Efficiency (%)	Direct Aerosol Deposition	Gravitational Settling Time
16	Stainless steel	645.16	Cellulose sponge	48.1	No	N/A
	Vinyl			25.6		
	Ceramic tile			48.9		
	Painted wood			25.5		
	Faux leather			30.3		
	Plastic			9.8		
17	Glass plates	100	Foam spatula vs wet-surface collector	9.9 – foam 15.2 – collector	Yes, compressed air nebulizer	16 h
18	Vectran fabric type A	400	Foam spatula	13.2	Yes, spray diffuser	15 min
	Vectran fabric type B			24.4		
	CFRP			57.1		
	Roughened CFRP			38.1		
	Vectran fabric type A		Polyester wipe	0.5		
	Vectran fabric type B			6.5		
	CFRP			9.0		
	Roughened CFRP			19.6		

CFRP, carbon fiber-reinforced plastic.

3. DISCUSSION AND CONCLUSIONS

The studies outlined within this literature review indicate that vacuum, swab, and wipe sampling can each be effective in the detection of biological threat agents dispersed via aerosol at low concentrations. However, to determine which method would be best to optimize recovery efficiency, multiple factors must be taken into consideration, including surface type, surface area, estimated amount of deposited contaminant, and limits of detection of each method. Additionally, research conducted in a controlled environment may not always best represent what would result in the event of a real-world contamination (20). Although there is no universally accepted set of rules for determining which collection method to use under varying circumstances, following general guidelines may be useful. Vacuum sampling can be effective in the detection of some biological threat agents dispersed via aerosol at relatively low concentrations, but it is often desirable to opt for swab or wipe methods instead, unless the surface area to be tested is very large. The swab sample collection method may be most

appropriate for sampling small areas (10–25 cm²) with high agent concentrations, and moist swabs are preferable to dry; however, which swab type optimizes recovery efficiency depends on the surface material being tested. The wipe sampling method often results in higher recovery efficiencies with lower limits of detection than vacuum or swab sampling and may be most practical for sampling larger areas (>25 cm²). Premoistened wipes are preferable to dry, but again, determining which wipe material to use to optimize recovery efficiency also depends on the surface material being tested. As an example, in a large study conducted by the EPA, the Department of Homeland Security Science and Technology Directorate (Washington, DC), and the CDC, swabs were used for small areas or hard-to-reach locations, such as heating, ventilation, and air conditioning supply diffusers or light fixtures; sponge-stick wipes were used over larger areas on nonporous surfaces; and vacuum socks were used over the largest areas for porous materials (21).

Gaps were identified in the body of research that was reviewed. Because the studies used such a wide variety of methodologies with differing surface types and areas, contamination procedures, and recovery protocols, it was often difficult to make direct comparisons between sampling methods and materials. As an example, there was no in-depth comparison of different wipe materials used to sample the same surface, under the same conditions, to recover the same agent. Additionally, no studies performed both surface sampling and direct aerosol sampling, making it very difficult to compare the two methods. Another gap was the variety of biological material reviewed. Most of the studies only conducted reviews on bacteria, specifically *B. atrophaeus*; no studies reported findings or research on sampling methods being used to detect viruses, and only two studies reviewed sampling methods used to recover ricin. In the studies reviewed, recovery efficiencies of toxins deposited via aerosol were either not significantly different between collection materials used or were below detectable limits, revealing the need for further research on sampling environments where toxin material may be deposited in this manner. Finally, although a variety of sampling surface areas, ranging from 1 to 2787 cm², were tested throughout the studies, and most resulted in positive recovery efficiencies showing that samples were able to be collected, we are unable to report on a minimum surface sampling size requirement to reach detection limits for common instruments such as PCR and ECL. Most of the experiments used only culture analysis to determine collection efficiencies, a few used PCR, and none used ECL.

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ACRONYMS AND ABBREVIATIONS

BDL	below detectable limit
BiSKit	biological sampling kit
Bkg	background
CARC	chemical agent resistant coating
CDC	Centers for Disease Control and Prevention
CFRP	carbon fiber-reinforced plastic
cfu	colony-forming units
ECL	electrochemiluminescence
EPA	Environmental Protection Agency
MCE	mixed cellulose ester
N/A	not applicable
PBC	polyester-bonded cloth
PCR	polymerase chain reaction
QPCR	quantitative polymerase chain reaction
SCRD	sample collection and recovery device
TECF	trace evidence collection filter

Blank

**APPENDIX:
MATERIAL COST**

Source	Material	Cost
2	Sterile polyester-rayon blend gauze wipe Sterile polyester-rayon blend gauze wipe Sterile polyester-rayon blend gauze wipe	\$678.22/case of 1000 \$177.50/5 cases of 100 \$8.94 for 50
3	Sterile rayon	Not listed
4	BiSKit	\$66.37 or \$59.74 (government price)
5	Sponge Macrofoam sponge	\$116.5/box of 100 \$12.50/unit (for 2000+ units)
6	Swab kit Cotton swab Sponge wipe Bulk sampling	Not listed \$231.50/case of 1000 Not listed \$181.00/pack of 2000
7	Vacuum socks 37 mm mixed cellulose ester filter cassette 37 mm polytetrafluoroethylene filter cassette Forensic evidence filter Gauze wipes	Not listed \$91.40/box of 50 \$445.00/pack of 50 \$357.00 \$83.83/case of 3000
8 and 9	Cotton tipped swabs Dacron-tipped swabs Rayon-tipped swabs Polyurethane macrofoam tipped swabs	\$319.50/case of 10 packs (1000/pack) \$66.50/pack of 100 Not listed \$504.64/case of 1000
10	Rayon-polyester blend wipes Polyethylene filter medium	\$203.52/case of 24 packs Not listed
11	Foam critical swabs Versalon all-purpose sponges Vacuum socks	\$419.10/case of 2500 \$83.82/case of 3000 Not listed
12	Polyester swab Gauze Kendall wipes SCRD paddles	\$295.87/case of 200 \$10.79/box of 100 \$12.50/unit (2000+ units)
13	Clean room cloths	\$146.45/case of 500
14	Cellulose sponge wipe	Not listed
15	Foam spatula Polyurethane macrofoam sponge wipe Polyester swab	Not listed Not listed Not listed
16	Swab Foam-spatula Nylon flocked-spatula SpongeSicle	\$468.95/case of 1000 Not listed Not listed Not listed
17	Wipe	\$342.81/case of 800
18	Cellulose sponge sampler	Not listed
19	Foam critical swabs Wipes Vacuum filtration sock	\$419.10/case \$14.65/bag of 200 Not listed
20	Cellulose sponge-stick wipes Swabs Vacuum socks	\$254.32 \$12.33/pack of 50 Not listed

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