



Identification and prioritisation of risk factors associated with *Listeria monocytogenes* in ready-to-eat food establishments through a harmonised official food control approach in Spain

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ABSTRACT

Implementing science-based interventions is vital for ensuring a risk-based official food safety control. The aim of this study was to investigate the prevalence of *Listeria monocytogenes* on surfaces in food establishments, identify risk factors for this hazard, and analyse the influence of these factors on the detection of the hazard in food establishments producing ready-to-eat (RTE) food in Spain between July 2024 and March 2025. A total of 184 inspection reports from various food sectors were studied, and 731 samples from food contact surfaces (FCS) and non-food contact surfaces (NFCS) were analysed. Prevalence, prevalence ratio and population attributable fraction were calculated. The results revealed a higher prevalence of *L. monocytogenes* on NFCS (22.5%) than on FCS (15.2%). The study identified critical risk factors associated with contamination. In particular, the ineffective separation between unprocessed and RTE areas was a significant factor for both surfaces. The highest risk factor influencing the presence of the hazard was unidentified stages of risk of cross-contamination with *L. monocytogenes*. This case study demonstrates how food control authorities can use science-based evidence to identify risk factors of *L. monocytogenes* and prioritise tailored interventions to effectively reduce this pathogen from food production environments.

1. Introduction

Official food safety control (henceforth, food control) is a pillar of public health, and it seeks to protect the health of consumers (FAO/WHO, 2013). While in the European Union (EU) food business operators (FBOs) are the legal agents responsible for implementing the law within their establishments, it is the responsibility of the designated food control authorities to verify whether FBOs correctly comply with it (EC 178/2002). If non-compliance is detected, food control authorities have the necessary powers to enforce the law through different administrative measures. The food control methods commonly employed include inspections, food sampling or audits (EU 2017/625).

In the EU, there is a legislative framework in place aiming at preventing listeriosis: Regulation 2073/2005 (EC 2073/2005) on microbiological criteria for RTE foods, and Regulation 852/2004 (EC 852/2004)

and Regulation 853/2004 (EC 853/2004) regarding hygiene requirements. Specifically, the cumulative incidence in Spain of this foodborne disease increased from 0.70 to 0.95 cases per 100,000 population between the period 2020 and 2024 (Instituto de Salud Carlos III, 2025). While the burden at a population level attributable to *Listeria monocytogenes* is lower compared to other hazards such as *Campylobacter* or *Salmonella*, the burden of the former at both population and individual levels is notably high (Pires et al., 2024). With respect to the monitoring of *L. monocytogenes* in food in Spain, the prevalence of this hazard in RTE foods has increased from 1.57% in 2022 to 1.77% in 2024. During the same period, meat and meat products were found to be the food with the highest prevalence of this hazard.

L. monocytogenes is a Gram-positive, non-spore-forming, non-encapsulated, facultative anaerobic, and rod-shaped bacterium that causes the foodborne disease named listeriosis. The microorganism is

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characterised by its high ubiquity in food environments and its ability to grow under refrigeration conditions due to its psychrotrophic nature. This pathogen is a prime concern in public health owing to the severe mortality rate associated with invasive listeriosis (Huang et al., 2023).

L. monocytogenes can colonise food environments and facilities and persist for long periods. The capacity of the pathogen to form and integrate into biofilm structures on surfaces of food facilities and equipment is a key factor in its high presence in food environments and represents a challenge for FBOs due to the difficulty of its eradication (Rohilla et al., 2024). The pathogen is more frequently detected in NFCS, such as floors, ceilings, drains, and walls, compared to FCS (Hua & Zhu, 2024a). Although NFCS are not intended to come into contact with food, personnel movement, food handling, splashing, and other events could lead to cross-contamination during production (Sauders & D'Amico, 2016). Contamination of equipment and processing environments has been linked to listeriosis outbreaks, across different RTE food sectors and often associated with persistent strains (Elson et al., 2019; Hua & Zhu, 2024; Nüesch-Inderbinen et al., 2021). Effective *L. monocytogenes* control programmes should include environmental monitoring to identify contamination sources and support appropriate cleaning and sanitation measures (Gupta & Adhikari, 2022). Therefore, further evidence is needed to determine which hygiene and operations conditions should be prioritised in the control of this pathogen in food processing environments.

Spain is administratively divided into 17 autonomous regions and 2 autonomous cities (Spanish Constitution). Each autonomous region and city have powers to carry out food control. At a national level, the Spanish Agency for Food Safety and Nutrition (AESAN) is responsible for coordinating and guiding all regional food control authorities (Spanish Law 17/2011). In addition, AESAN is responsible for all draft legislation relating to food safety. This includes preparing domestic legislation or transposing EU directives into the Spanish legal framework.

In response to the rising prevalence of *L. monocytogenes* in food and human incidence of listeriosis in Spain, AESAN and the regional food control authorities implemented the so-called 'Coordinated control plan for *L. monocytogenes*' in 2024. This plan aimed to harmonise the official control interventions in order to improve the effectiveness of the risk management of *L. monocytogenes* in RTE producing food establishments. Highlighting that it is necessary to collect data to support precise and effective food control interventions in this field, as part of the above plan, the present study aimed 1) to investigate the prevalence of *L. monocytogenes* environments of producing RTE foods establishments, 2) to study the relationship between the detection of *L. monocytogenes* in environmental samples and the detection of non-compliances to identify risk factors associated with the presence of *L. monocytogenes*, and 3) to prioritise risk factors that should be addressed during inspections so that they are more effective in reducing the risk of *L. monocytogenes* contamination.

2. Materials and methods

2.1. Study design, population and source of information

A cross-sectional study was carried out between July 2024 and March 2025 to assess the prevalence of *L. monocytogenes* on surfaces in food establishments producing RTE foods in Spain. The study included a total of 184 food establishments registered in the Spanish General Health Register of Food Companies and Foods that manufactured, portioned and/or packaged RTE foods. The food categories included in the study were prepared meals, fish products, meat products, dairy products, vegetable products and egg products.

The content of 184 inspection reports (1 per establishment) elaborated during inspections carried out without prior notice was assessed, of which 65 (35.3%) were from meat product establishments, 52 (28.3%) from dairy products, 27 (14.7%) from prepared foods, 25 (13.6%) from fishery products, 13 (7.1%) from vegetable products and 2

(1.1%) from egg products. A total of 731 of environmental samples were collected and analysed: 442 (60.5%) from FCS and 289 (39.5%) from NFCS.

2.2. Harmonised inspection protocol

For the identification of non-compliances associated with *L. monocytogenes* risk, a harmonised inspection protocol consisting of a checklist was developed through the collaboration between representatives from regional food control authorities and AESAN. This tool was subsequently ratified by all 17 Spanish regional food control authorities to ensure national consistency during official inspections. To ensure consistent interpretation and use of the inspections protocol, training of control officers was conducted both, from AESAN, through sharing written instructions and criterion to assess compliance, as well as from the regional food control authorities, through practical sessions on how to use the protocol and to sample surfaces.

The final version of the checklist comprised a total of 60 questions divided into the following six sections (Supplementary material): 1) general information regarding the type of food establishment (2 questions), 2) food safety management (7 questions), 3) verification of facilities, surfaces and equipment (16 questions), 4) verification of cleaning and disinfection (17 questions), 5) verification of environmental monitoring sampling (12 questions), and 6) sampling of surfaces (6 questions). Control officers were required to complete this assessment during each inspection and specifically document the sampling points.

2.3. Environmental sampling and analysis

Official environmental samples were collected from both FCS and NFCS. At least two samples were taken per establishment: one from FCS and another from NFCS. To assess the risk of contamination during production, sampling was preferably conducted during operating hours and specifically up to 2 h after the start of activity. Control officers selected the sampling points following a detailed assessment of the FBOs' food safety management system. Priority was given to stages identified as posing a higher risk of contamination or growth of *L. monocytogenes*, including post-lethal exposure stages. Sampling was carried out in accordance with the 'EURL Lm Technical Guidance Document on sampling the food processing area and equipment for the detection of *L. monocytogenes*' (Midelet et al., 2023). After collection, samples were maintained at 1–8 °C and transported to the laboratory in insulated containers capable of maintaining this temperature range. Samples were analysed within a maximum of 24 h after collection and were not frozen before analysis.

Microbiological analyses were performed in laboratories designated by the competent authorities for food control and accredited according to ISO/IEC 17025. Detection of *L. monocytogenes* was carried out using the ISO 11290-1 reference method. In some cases, real-time PCR or enzyme-linked fluorescent assay (ELFA) was used as a preliminary screening method. However, any presumptive positive result required subsequent isolation and confirmation of *L. monocytogenes* according to ISO 11290-1 before the sample was reported as positive.

2.4. Statistical data analysis

To identify the risks associated with the presence of *L. monocytogenes*, a structured statistical approach was implemented. The dependent variable was defined as the microbiological result of sampling categorised as either 'detection' or 'non-detection' of *L. monocytogenes* for at least one of the samples collected per establishment and surface type. The independent variable was defined as the compliance status for each question of the checklist categorised as 'compliant' or 'non-compliant'.

Firstly, the prevalence of *L. monocytogenes* was calculated as well as its respective 95% confidence intervals (95% CI). Its distribution was described using absolute (N) and relative (%) frequencies stratifying by

food sector and surface type. Confidence intervals for prevalence estimates were calculated using the Wilson method (Brown et al., 2001), as this provides more accurate coverage for binomial proportions, especially when sample sizes are small or observed prevalence rates are low. Secondly, we compared the detection of *L. monocytogenes* against the detection of non-compliance for each question of the checklist by using proportions and stratifying by surface type. The association between environmental non-compliances and the detection of *L. monocytogenes* was evaluated using Pearson's chi-squared tests. To assess the magnitude of these associations, prevalence ratios (PR) and their respective 95% CI were determined (Equation (1)). We selected PR as the measure of association because it is more consistent and easier to interpret than alternative measures, such as odds ratio or prevalence odds ratio, and they avoid overestimating the strength of the association (Espelt et al., 2019; Schiaffino et al., 2003). Furthermore, for cross-sectional studies with binary outcomes, using PR is recommended over prevalence odds ratio (Martinez et al., 2017; Thompson et al., 1998; Zocchetti et al., 1997).

$$\text{Prevalence ratio (PR)} = \frac{P_{\text{Listeria monocytogenes detection} \mid \text{non-compliant}}}{P_{\text{Listeria monocytogenes detection} \mid \text{compliant}}} \quad \text{Equation 1}$$

$P_{\text{Listeria monocytogenes detection} \mid \text{non-compliant}}$ is the prevalence of *L. monocytogenes* in establishments failing a checklist question and $P_{\text{Listeria monocytogenes detection} \mid \text{compliant}}$ is the prevalence of those meeting the requirement. A PR > 1 indicated that the detection of *L. monocytogenes* was higher when detecting non-compliance. All questions of the checklist having a PR greater than 1 were considered as potential risk factors.

Finally, we estimated the population attributable fraction (PAF) expressed as percentage and its 95% CI for each potential risk factor. Results indicate the proportion of cases of detecting *L. monocytogenes* that could be prevented when eliminating the exposure to the potential risk factor in question. In this case, CI were calculated as suggested by Ferguson and O'Connell (2024). PAF was selected as the primary prioritisation metric because it reflects both the strength of the association and the prevalence of the exposure in the population, thereby estimating the proportion of cases of *L. monocytogenes* that could potentially be prevented if the exposure were eliminated (Khosravi et al., 2021; Mansournia & Altman, 2018). Unlike measures of association alone, PAF provides an estimate of the potential population-level impact of addressing a risk factor and is therefore particularly useful for prioritising public health interventions and preventive strategies.

The Stata 15.1 software (StataCorp LLC, College Station, TX, USA) was used for the statistical analyses as well as calculating the PR and PAF. A p-value of <0.05 was considered statistically significant for all statistical tests. The RStudio version 2024.04.0 + 735 software (RStudio Team, 2020) was used to create the figures.

3. Results

3.1. Prevalence and distribution of *L. monocytogenes*

Overall, the prevalence of *L. monocytogenes* in FCS was 15.2% [95% CI: 10.4-21.5], while in NFCS it was 22.5% [95% CI: 16.3-29.7] (Table 1). Of all establishments, the highest prevalence of *L. monocytogenes* in FCS was found in egg product establishments (50.0%) and equally followed in both meat (23.1% [95% CI: 13.7-35.4]) and vegetable product establishments (23.1% [95% CI: 5.0-53.8]). However, with respect to the egg product establishments, it is important to note the small sample size, as only two establishments were inspected. Contrary, in NFCS, the highest prevalence of *L. monocytogenes* was in establishments producing vegetable products (30.8% [95% CI: 9.1-61.4]), followed by meat products (29.8% [95% CI: 18.4-43.1]) and prepared meals (26.9% [95% CI: 11.3-47.8]).

3.2. Association between environmental control variables and *L. monocytogenes* detection

In relation to the food safety management section, in those establishments where *L. monocytogenes* was detected on FCS, a significant association was identified with the fact that this microorganism was not included in the hazard analysis (PR = 2.33 [95% CI: 1.12-4.87]) (Fig. 1). In NFCS, detecting *L. monocytogenes* was statistically significant associated with the possibility of recontamination after the critical control point (PR = 2.45 [95% CI: 1.29-4.67]).

The detection of *L. monocytogenes* with respect to the verification of facilities, surfaces and equipment section showed the highest PR in both surfaces, FCS (PR = 2.23 [95% CI: 1.09-4.55]) and NFCS (PR = 2.46 [95% CI: 1.42-4.28]). In FCS, it was associated with not having an effective separation between areas for unprocessed and RTE products (Fig. 2).

In NFCS, other situations resulted to be statistically associated with detecting *L. monocytogenes*. Those included having fixed equipment not located far enough away from the walls of the processing areas or from the floor (PR = 2.45 [95% CI: 1.29-4.67]) followed by not controlling personnel flows (PR = 2.23 [95% CI: 1.29-3.85]), not identifying stages of risk of cross-contamination of *L. monocytogenes* (PR = 2.20 [95% CI: 1.28-3.79]), not designing process flows to minimise the risk of cross-contaminations (PR = 2.06 [95% CI: 1.19-3.6]) and not identifying post-lethal exposure environments (PR = 1.88 [95% CI: 1.08-3.29]).

In the section of verification of cleaning and disinfection, in those establishments where identification was not in place of facilities, equipment and tools to be cleaned and disinfected there was an association with detecting *L. monocytogenes* in NFCS (PR = 1.99 [95% CI: 1.06-3.71]) (Fig. 3). With regards to the verification of the

Table 1

Prevalence of *Listeria monocytogenes* in food establishments where *Listeria monocytogenes* was detected at least in one sample by type of sector and surface. In the same establishment, samples could be taken from both food (FCS) and non-food contact surfaces (NFCS).

Food sector	Food contact surfaces (FCS) ^a			Non-food contact surfaces (NFCS) ^b		
	Establishments (n)	Detection of <i>Listeria monocytogenes</i> (n)	Prevalence (95% CI) ^c	Establishments (n)	Detection of <i>Listeria monocytogenes</i> (n)	Prevalence (95% CI) ^c
Meat products	65	15	23.1 (13.7 - 35.4)	57	17	29.8 (18.4 - 43.1)
Dairy products	52	2	3.9 (0.5 - 13.2)	48	6	12.5 (4.7 - 25.2)
Prepared meals	27	3	11.1 (2.4 - 29.2)	26	7	26.9 (11.3 - 47.8)
Fishery products	25	4	16.0 (4.5 - 36.1)	24	4	16.7 (4.7 - 37.4)
Vegetable products	13	3	23.1 (5.0 - 53.8)	13	4	30.8 (9.1 - 61.4)
Egg products	2	1	–	1	0	–
Total	184	28	15.2 (10.4 - 21.5)	169	38	22.5 (16.3 - 29.7)

^a Equipment (e.g. mincer, slicer, packaging machine or mixer), worktables, utensils, cutting boards, conveyor belts and trolleys.

^b Drains, equipment (e.g. non-contact parts of packaging machines, weighing machines, centrifuges or slicers), trolleys, doors, floors, conveyor belts, tables, pallets, ceilings, cleaning utensils and cold rooms.

^c Confidence intervals.

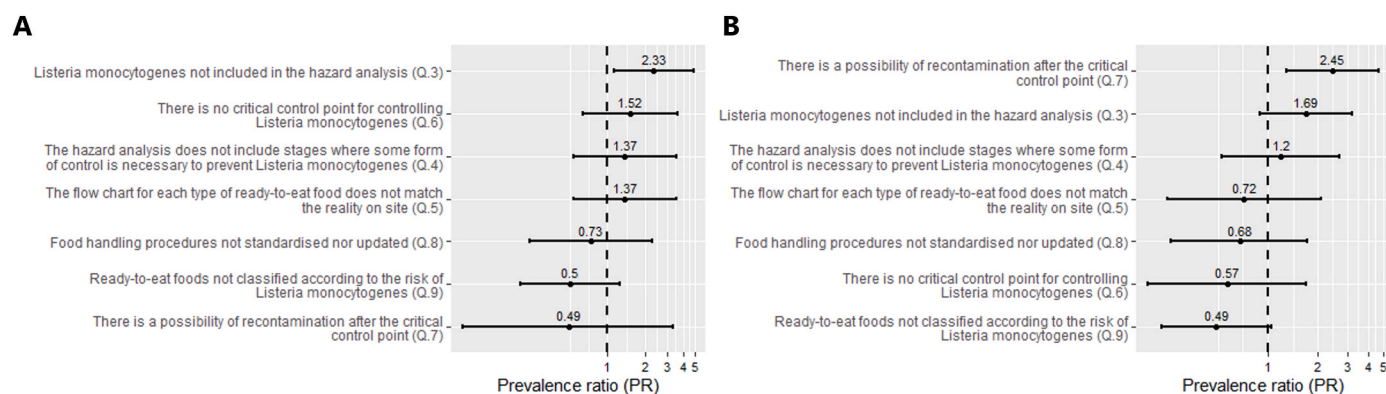


Fig. 1. Prevalence ratio (PR) of detection of non-compliance with the section on food safety management (section 2) and detection of *Listeria monocytogenes*. A, Food contact surfaces (FCS) (n = 184); B, Non-food contact surfaces (NFCS) (n = 169).

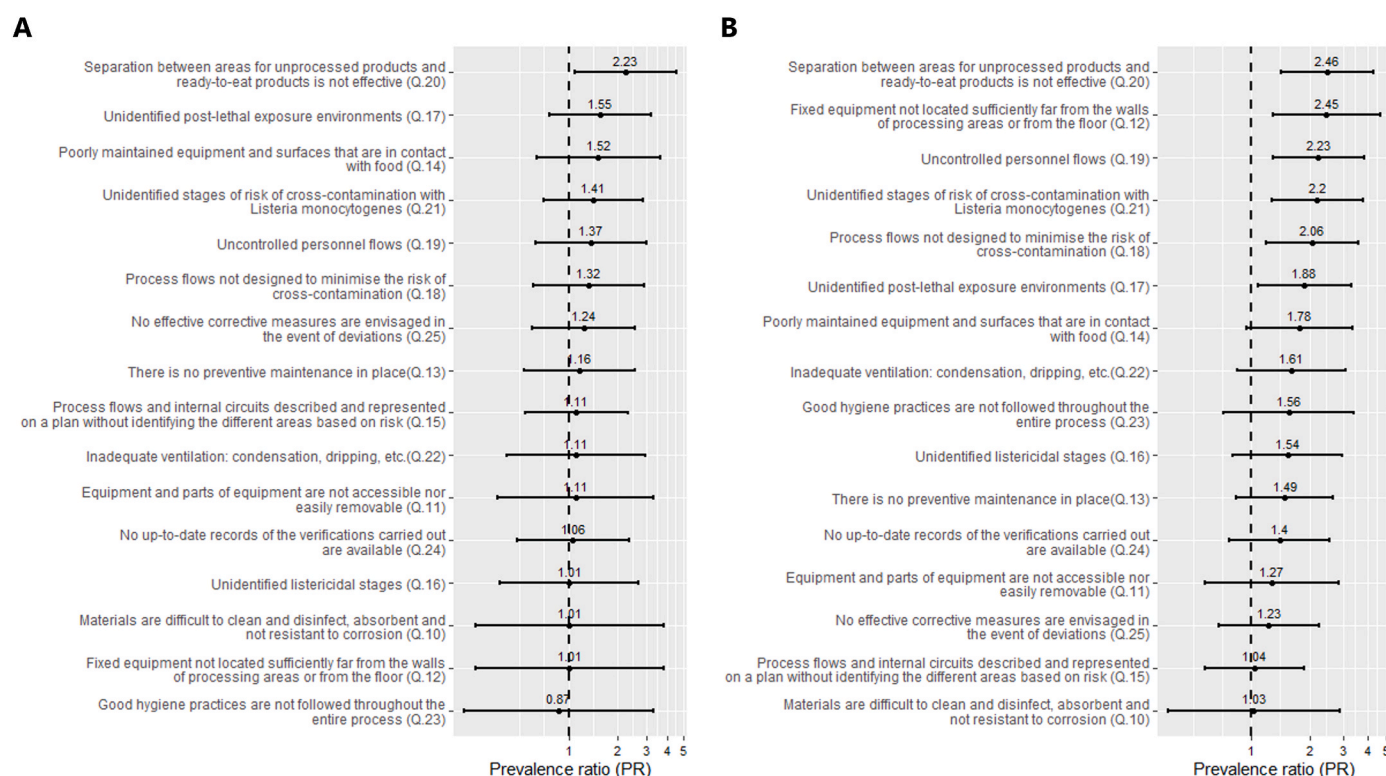


Fig. 2. Prevalence ratio (PR) of detection of non-compliance with the section on verification of facilities, surfaces and equipment (section 3) and detection of *Listeria monocytogenes*. A, Food contact surfaces (FCS) (n = 184); B, Non-food contact surfaces (NFCS) (n = 169).

environmental monitoring sampling section, no aspects were identified as having a statistical association with the detection of *L. monocytogenes* in either FCS or NFCS (Fig. 4).

3.3. Prioritisation of risk factors for *L. monocytogenes*

Among the different risk factors identified (Table 2), FCS having fixed equipment not located far enough away from the walls of the processing areas or from the floor had the highest PAF (PAF = 15.75% [95% CI: 1.36–35.10]). On the other hand, with respect to NFCS, not having identified the risk cross-contamination stages with *L. monocytogenes* had the highest PAF (PAF = 25.88% [95% CI: 7.52–44.75]).

4. Discussion

This study assessed the prevalence of *L. monocytogenes* in RTE food establishments in Spain and identified key risk factors associated with environmental contamination and their attributable impact. The results are consistent with previous studies describing the ecology and persistence of *L. monocytogenes* in food processing environments, with higher detection of this pathogen on NFCS than on FCS. To our knowledge, this is the first study to combine food control data with microbiological results from official sampling to identify risk factors for environmental contamination in that manner. Additionally, we propose the use of a methodology that has not been generally applied in food control practice to prioritise inspection interventions. Acknowledging the practical relevance of our study, it could potentially influence how *L. monocytogenes* is approached at national and regional levels in Spain towards a more targeted science-based inspections and hygiene

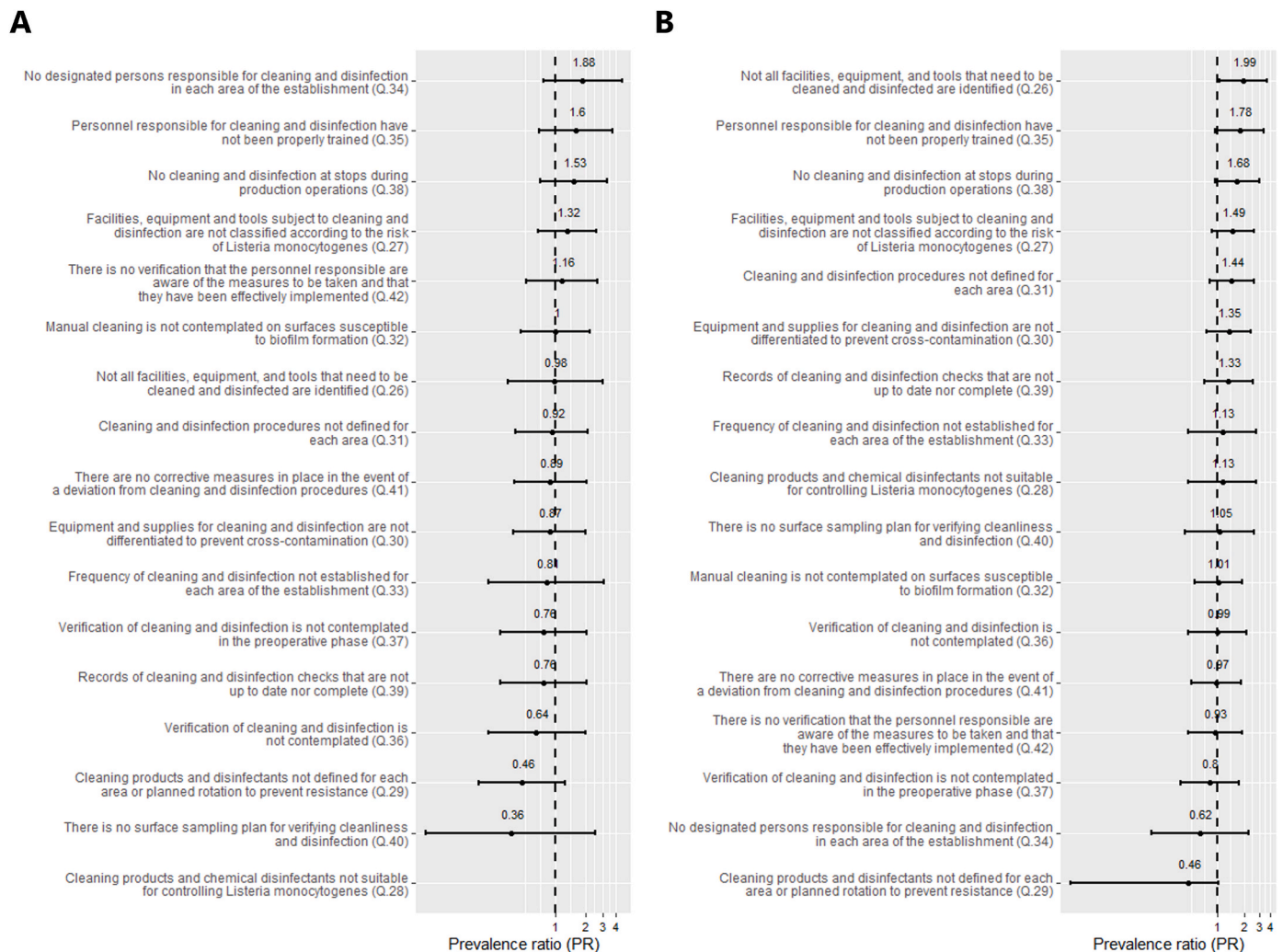


Fig. 3. Prevalence ratio (PR) of detection of non-compliance with the section on verification of cleaning and disinfection (section 4) and detection of *Listeria monocytogenes*. A, Food contact surfaces (FCS) (n = 184); B, Non-food contact surfaces (NFCS) (n = 169).

management strategies.

4.1. Prevalence of *L. monocytogenes* in different food processing environments

The higher prevalence of *L. monocytogenes* in NFCS found for all types of establishments was expected, owing to the environmental ubiquity of this genus, that can be present in drains, floor, equipment framework and surfaces, and walls (Chowdhury & Anand, 2023; Diaz et al., 2025). These findings are consistent with previous studies identifying the NFCS as the primary reservoir where *Listeria* spp. can survive and persist compared to FCS (Tirloni et al., 2020). In addition, NFCS often hosts stable resident microbiota including *Pseudomonas* spp., which can form biofilms that protect *Listeria* cells from routine cleaning and disinfection procedures (Diaz et al., 2025).

The varying incidence across food sectors found in this study may not be linked to commodity type, but rather to differences in sanitation programmes, the effectiveness of the disinfectants used (Hua et al., 2019), and the implementation level of environmental monitoring plans concerning *L. monocytogenes* (Ruiz-Llacsahuanga et al., 2021). Moreover, differences in sampling frequency and number could have contributed to the higher number of positive establishments in one sector over others, as is the case with the egg sector (50% positive). Results for the meat (n = 65) and dairy (n = 52) sectors are deemed to be more robust than those for the vegetable sector, with only 13 inspected

establishments. Despite the more intensified sampling of premises in the dairy sector, a lower presence of *L. monocytogenes* was registered for both types of surfaces, though it was higher for NFCS (12.5%). Dairy products have been related to relevant listeriosis outbreaks, attributed to cheese and ice cream. Moreover, NFCS has been identified as a contamination source in listeriosis cases. For the meat sector, the number of establishments showing contaminated surfaces was consistently high, with more establishments having positive NFCS samples (29.8%). This increased presence of *L. monocytogenes* has been widely reported on both types of surfaces, although the trend could vary among studies, in some cases, with more prevalence in FCS (12.9%) (Centorotola et al., 2021; Possas et al., 2021; Rodríguez-López et al., 2020). These processing environments are characterised by high levels of proteins and fats, which can protect bacteria from the action of sanitisers and facilitate biofilm formation.

The vegetable sector establishments showed a high percentage of premises with contaminated surfaces, showing similar levels to those recorded in meat-producing facilities (FCS = 23.1% and NFCS = 30.8%). The agricultural environment is the natural niche of *L. monocytogenes*. Therefore, handling raw vegetable materials leads to higher contamination rates in facility environments. The organic load and material associated with the specific fruit and vegetable are drivers in environmental contamination. For instance, NFCS in processing facilities of fresh-cut mushrooms, accumulating solid particles from soil, exhibited 19% of contamination rate by *L. monocytogenes*, though for tree fruit

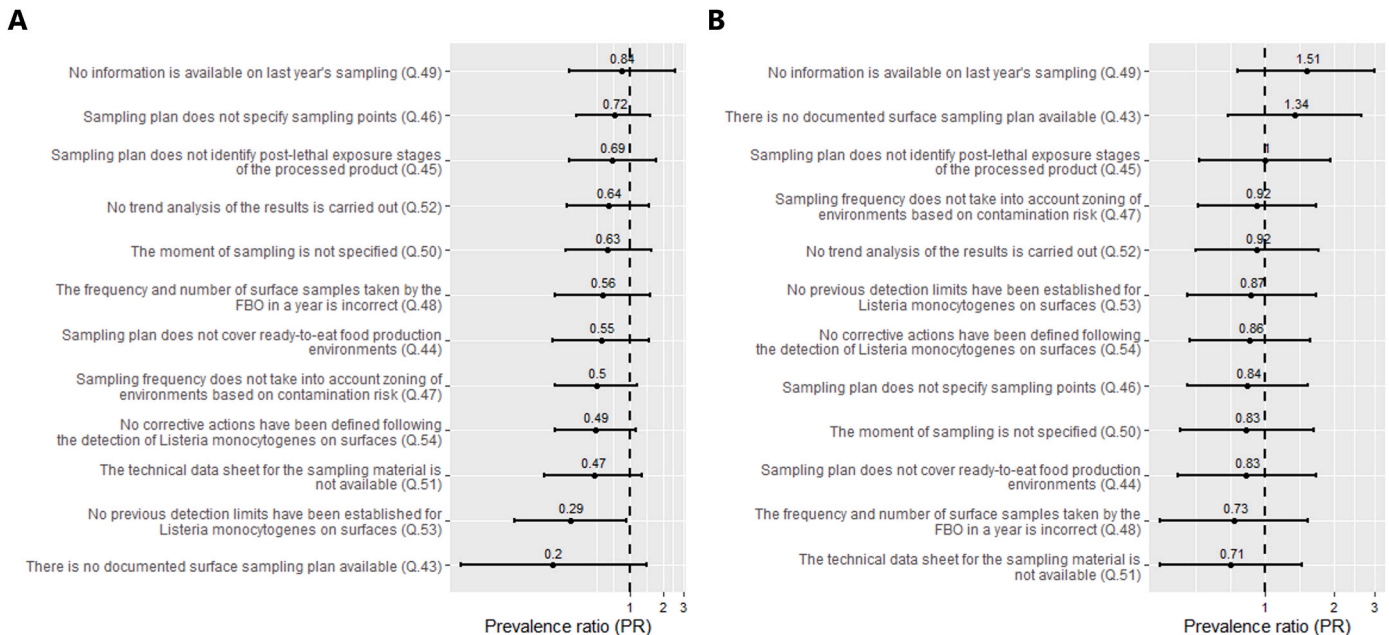


Fig. 4. Prevalence ratio (PR) of detection of non-compliance with the section on verification of environmental monitoring sampling (section 5) and detection of *Listeria monocytogenes*. A, Food contact surfaces (FCS) (n = 184); B, Non-food contact surfaces (NFCS) (n = 169).

Table 2
Population attributable fraction (PAF) of the risk factors identified for *Listeria monocytogenes* by type of surface.

Type of surface	Risk factors	Population attributable fraction (%) (95% CI ^a)
Food contact	Separation between areas for unprocessed products and ready-to-eat products is not effective (Q.20)	15.75 (1.36 - 35.10)
	<i>Listeria monocytogenes</i> not included in the hazard analysis (Q.3)	14.29 (1.46 - 32.59)
Non-food contact	Unidentified stages of risk of cross-contamination with <i>Listeria monocytogenes</i> (Q.21)	25.88 (7.52 - 44.75)
	Uncontrolled personnel flows (Q.19)	18.84 (5.13 - 35.07)
	Separation between areas for unprocessed products and ready-to-eat products is not effective (Q.20)	17.19 (5.59 - 31.75)
	Process flows not designed to minimise the risk of cross-contamination (Q.18)	17.64 (3.60 - 34.31)
	Unidentified post-lethal exposure environments (Q.17)	17.26 (1.84 - 43.70)
	Not all facilities, equipment, and tools that need to be cleaned and disinfected are identified (Q.26)	10.46 (0.74 - 24.28)
	There is a possibility of recontamination after the critical control point (Q.7)	9.35 (2.00 - 20.69)
	Fixed equipment not located sufficiently far from the walls of processing areas or from the floor (Q.12)	9.35 (2.00 - 20.69)

^a Confidence intervals.

processing facilities, the same study reported values especially high (NFCS = 56.4%) (Ruiz-Llacsahuanga et al., 2021). Establishments in the fish sector exhibited a more uniform distribution of *L. monocytogenes* compared to other sectors, with approximately the same prevalence on FCS (16.0%) and NFCS (16.7%). Results of a global meta-analytical study suggest that the processing environment and extensive handling are primary drivers of contamination in the fish sector, with a higher prevalence of *L. monocytogenes* found in RTE fish products (14.5%), compared to raw fish (5.8%) (Zakrzewski et al., 2024). Standard processing steps, such as salting, are not enough to totally mitigate the pathogen, due to its capacity to persist in high salt environments, such as

brine and brine containers (Gudmundsdóttir et al., 2005). Moreover, fish skinning and slicing operations have been identified as critical cross-contamination points, with slicing machines often showing the highest contamination rates among FCS (Tocmo et al., 2014).

4.2. Toward a science-based environmental food control programmes in Spain

Based on Regulation 2017/625 (EU 2017/625) on official controls and other official activities performed to ensure the application of food and feed law, food control interventions should be risk-based. The World Health Organization defines the concept of ‘risk-based inspection’ as ‘activities focused on food products and legal food businesses that pose the highest risk to consumers’ health’ (WHO, 2024). To mitigate the risk of exposure, food control interventions should target and prioritise high-risk FBOs (Garcia Martinez et al., 2013), for example through higher inspection frequency or enforcing more severe administrative measures when high risk is detected. Identifying the non-compliances most strongly associated with the presence of *L. monocytogenes* can support science-based food control in recognising higher-risk establishments and applying appropriate administrative measures.

Guiding food control through science-based evidence will positively contribute to implement more effective and consistent food control, key principles according to Regulation 2017/625 (EU 2017/625) and Codex Alimentarius at the international level. The ability of control officers to identify non-compliances is expected to increase as a result of more specific attention to those conditions linked to the presence of *L. monocytogenes*, thereby improving the overall effectiveness of control activities (Berkling et al., 2019). Moreover, addressing the specific non-compliances identified as risk factors will help control officers to provide FBOs with more precise guidance and facilitate the prompt correction of non-compliant situations (Läikkö-Roto et al., 2015). As discussed by Vachon et al. (2025), evidence-based practices were key to ensure a successful capacity building of frontline public health professionals to improve detection and reporting of foodborne illness in the United States of America.

Consistency will help to assess the risk of non-compliance systematically from inspection to inspection and between control officers (Lundén et al., 2021). Standardising the administrative measures

applied in equivalent risk situations may contribute to more uniform and comparable enforcement and to the consistent treatment of FBOs (Kettunen et al., 2017), resulting in higher satisfaction and trust in food control authorities and the overall food control system (Kaskela et al., 2019). Standardisation is also a key component in the implementation of digital environments to support control officers and improve consistency and interpretability in inspection decision-making (Grau-Noguer et al., 2024). Barcelona city is highlighted as an example of this approach (FAO, 2024).

The results of this study could also be used as evidence-based indicators to prioritise resource allocation. Human and economic resources could be more accurately directed towards interventions targeting FBOs where the non-compliances showing the strongest associations with *L. monocytogenes* detection are identified. Similarly, the results could support the allocation of funding for the training of control officers. In other food safety domains, targeted funding for training has been shown to improve the detection and reporting of foodborne outbreaks (Vachon et al., 2025).

The findings of this study may also contribute to hygiene management education by providing empirical evidence from food control on the practices most strongly associated with *L. monocytogenes* detection. The application of quantitative measures such as PR and PAF provides a means of translating inspection findings into practical risk-management interventions. Beyond inspection prioritisation, the methodology promotes a shift from a compliance-based towards a data-based learning approach, by quantitatively assessing the relationship between specific hygiene situations and the presence of *L. monocytogenes*. A significant advantage of this methodology is its practicality and potential integration into routine food control, as it can be periodically applied when new inspection data becomes available. This would facilitate continuous evaluation of the relationship between non-compliances and *L. monocytogenes* detection and support the identification of emerging patterns over time. The findings may also be relevant to other stakeholders, including FBOs and academia. In this line, the results of this study were presented to FBOs in Spain to strengthen their management systems for the control of this hazard and their response was positive.

The implementation of risk-based scores and a grading system in food inspection has been shown to promote food safety and raise awareness of risk factors (da Cunha et al., 2016). These systems are usually supported by compliance checklists in which higher points are deducted for high-risk non-compliances (Makofske, 2020). Such scoring systems may also contribute to greater consistency, as inspection outcomes directly inform subsequent actions, including enforcement measures and inspection frequency (Borraz et al., 2022). Food premises grading systems are commonly based on risk factor criteria classified into hygiene practices, facility conditions, and management controls. The weights assigned to these criteria should be supported by scientific evidence to ensure that premise classification reflects the relative relevance of each risk factor. Accurate classification is essential to prioritise inspections, allocate resources and develop suitable control measures (FAO, 2008). The significant associations identified in this study could support assigning greater weight to criteria related to facility conditions and management control, particularly those concerning the identification of contamination routes and sources and the implementation of appropriate prerequisite control measures.

4.3. Impact of environmental control practices on *L. monocytogenes* exposure

The effectiveness of environmental control practices is an important factor associated with the prevalence of *L. monocytogenes* in food establishments (Rolon et al., 2025). As observed in this study, the establishment with the highest prevalence of *L. monocytogenes* lacked a formal environmental monitoring programme. Although compliance with basic regulatory requirements is key to achieving an adequate level of safety, it does not guarantee that the pathogen is absent within the processing

environment. Science-based environmental monitoring programmes allow identifying persistence niches of *L. monocytogenes* and its contamination routes within an establishment, providing actionable information beyond regulatory compliance.

The most significant checklist-recorded non-compliance identified in NFCS was the lack of identified stages for cross-contamination risk (PAF 25.88%), followed by production process flows recorded as not designed to minimise cross-contamination (PAF 17.64%). These results indicate an association between these checklist-recorded non-compliances and the detection of *L. monocytogenes*. They should not be interpreted as a direct assessment of the establishments' process flows or as evidence that these factors caused the contamination. However, they may help to identify aspects requiring further establishment-specific investigation, including potential pathogen routes and post-lethality stages where products may be exposed to *L. monocytogenes*. Where such routes are confirmed, tailored mitigation strategies, including a 'seek-and-destroy' process (Malley et al., 2015), may be implemented.

Ineffective separation between unprocessed and RTE areas was identified as a relevant checklist-recorded non-compliance for both FCS (PAF 15.75%) and NFCS (PAF 17.19%). Failure to separate these areas may facilitate the reintroduction of *L. monocytogenes* from raw materials or the external environment into production zones. This potential movement may also be favoured by uncontrolled personnel flows, which were associated with *L. monocytogenes* detection on NFCS (PAF 18.84%). Therefore, zoning areas according to their contamination risk can help establish physical and operational barriers and control mobile vectors, such as operator boots, trolley wheels and equipment moved between areas, thereby limiting opportunities for cross-contamination in processing environments (Malley et al., 2015; Tirloni et al., 2020).

From an exposure-assessment perspective, the findings of our study may also contribute to the development of more realistic scenarios for quantitative microbial risk assessments. Checklist-recorded non-compliances related to separation between unprocessed and RTE areas, post-lethal exposure, personnel flows and potential cross-contamination routes may help to define relevant contamination scenarios and to identify processes requiring more detailed quantitative investigation. However, the present study did not quantify *L. monocytogenes* concentrations, transfer rates between surfaces and foods and vice-versa, contamination frequencies, subsequent growth or consumer exposure. Therefore, the estimated PR and PAF values cannot be interpreted as direct estimates of consumer risk or risk reduction. Future studies combining harmonised inspection data with concentration, transfer and exposure data could help to quantify how conditions observed in food manufacturing environments influence *L. monocytogenes* exposure through RTE foods.

4.4. Strengths and limitations

This study has several strengths. First of all, to our knowledge, it is the first study aiming to increase the science behind food control interventions by combining inspection data with microbiological official environmental sampling results in order to identify risk factors associated with *L. monocytogenes* contamination in RTE food establishments. In this line, this study offers a real-world example of how food control data can be analysed to support more effective and scientifically justified interventions. The large national dataset, together with the implementation of a harmonised inspection protocol, provides a comprehensive overview of the current situation in Spain on this matter and supports a consistent and evidence-based approach to food control. These findings are directly relevant to food control authorities and could inform the development of more targeted and consistent interventions. However, several limitations should be considered. Due to the cross-sectional study nature of this study, the identified associations should not be interpreted as causal relationships. Furthermore, while the statistical analyses identified risk factors associated with *L. monocytogenes* detection, the absence of multivariable modelling limited our ability to

account for potential confounding factors and identify independent predictors of contamination. Additional information such as the size of the food processing environments, the number of food handlers or other information related to the nature of the FBOs would potentially allow further statistical analysis. Moreover, environmental sampling locations were selected by control officers alone based on perceived risk during the inspections, rather than through a standardised random sampling strategy. This targeted approach may have involved selection bias and influenced the estimated prevalence of *L. monocytogenes*. Additionally, the representation of some food sectors by relatively few establishments limited the robustness of sector-specific estimates. Finally, the study only assessed the presence or absence of *L. monocytogenes*, not including quantitative microbiological data or strain characterisation. This meant that additional information on contamination levels, persistence and potential transmission pathways was not available. As food production systems, regulatory frameworks and food control programmes vary between countries, this study's findings may not be generalisable to other regions and therefore extra care is needed when making inferences of them.

5. Conclusions and future work

Using a harmonised inspection protocol at a national level has proven to be very useful in ensuring consistent inspections, with all control officers using the same checklist and criteria to judge the law compliance of FBOs, and to collect accurate food control data accordingly. This has allowed statistical analysis to be applied to the results, yielding scientifically supported conclusions. In our opinion this is very unusual in the field of food control. This forms the basis to support a science-based, common and systematic approach for all regional and local food control authorities at national level to address *L. monocytogenes*. Moreover, it will enable a more effective and consistent food control in this area. The risk factors for the presence of *L. monocytogenes* identified were statistically significant and consistent with those reported in the scientific literature for the environmental persistence of the pathogen in question in food production areas. As a result, regional food control authorities reported satisfaction with the methodology used in this food control plan, noting that it yielded more reliable and informative results than previous national plans, which relied on a compliance-based approach rather than a data-based one. We recommend that this methodology should be further applied to other food control areas. In addition, in countries where food control is decentralised and managed by regional or local food control authorities such as Spain, food control should rely on harmonised inspection frameworks ensuring greater consistency during inspections as well as facilitating the collection of valid and comparable data at national level.

Future work should focus on continuing to collect data on the presence of *L. monocytogenes* and the detection of non-compliances, in order to assess the consistency of the results over time. Besides, it would be useful to collect data on the characteristics of FBOs, such as the number of employees or the volume of food produced and sold, to better identify and differentiate high-risk FBOs. In addition, future research may assess the impact of implementing the 'Coordinated control plan for *L. monocytogenes*' on listeriosis outbreaks and cases in humans, as well as studying the satisfaction of control officers from the regional food control authorities with using a harmonised checklist at a national level and the methodology to measure the association with *L. monocytogenes* and prioritise interventions.

CRediT authorship contribution statement

E. Grau-Noguer: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F. Pérez-Rodríguez:** Writing – review & editing, Writing – original draft, Investigation. **A. Possas:** Writing – review & editing, Writing – original draft, Investigation. **C. Ocerín:**

Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodcont.2026.112700>.

Data availability

The authors do not have permission to share data.

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