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Evaluating food safety management systems in Singapore: A controlled interrupted time-series analysis of foodborne disease outbreak reports

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ABSTRACT

Food catering service establishments are often implicated in foodborne disease outbreaks. We evaluated the effects of implementing Food Safety Management Systems (FSMS) in food catering service establishments in Singapore on two outcome measures: foodborne disease outbreaks and food hygiene violations. Using a controlled interrupted time-series study design, we estimated the change in the average level of these outcome measures following implementation, and compared the pre- and post-intervention trends. There were 42 foodborne disease outbreaks and 521 food hygiene violations associated with catering service establishments from 2012 to 2018. Eighteen months after FSMS implementation, we observed a 78.4% decrease (IRR: 0.216, 95% CI: 0.050 to 0.940, $p = 0.041$) in the average level of foodborne outbreaks in food catering service establishments. There was no significant effect on reported hygiene violations. Our study suggests that the FSMS implementation was successful in reducing foodborne outbreaks.

1. Introduction

Foodborne diseases impose a considerable public health burden across the globe. According to the World Health Organization, almost 600 million episodes of diarrhoeal disease in 2010 were attributable to contaminated food, resulting in 25 million Disability Adjusted Life Years (Kirk et al., 2015). The global public health impact is disproportionate, with approximately 217 million episodes occurring in children under 5-years of age (Kirk, Angulo, Havelaar, & Black, 2017) and the African and South East Asian regions bearing the highest burden (Kirk et al., 2015). Contributing factors for foodborne outbreaks have been reported to include improper cooking, contaminated ingredients, cross contamination and improper storage (Wu et al., 2018). Although food catering services are not the major cause of foodborne outbreaks, they often generate a disproportionately higher number of foodborne illness cases. In the United States, food catering services were implicated in 14% of all reported food service associated outbreaks but accounted for 22% of all outbreak associated illnesses (Centers for Disease Control and Prevention, 2017). In Australia, commercial catering establishments were implicated in 9% of all reported foodborne disease outbreaks but accounted for 18% of all outbreak related illness cases (OzFoodNet Working Group, 2015). Improving food safety systems remains an important priority for health authorities seeking to reduce the burden of foodborne disease.

A food safety management system (FSMS) aims to systematically identify and eliminate physical, chemical and microbiological contamination in the production process to ensure that food is safe for consumption (ISO, 2005). In 2005, the International Organization for Standardization (ISO) developed the auditable standard ISO 22000 which specified the requirements for a FSMS based on HACCP principles, system management and interactive communication and prerequisite programs. Proper storage, regular cleaning, waste management, timely equipment maintenance and pest management are examples of prerequisite programs commonly used to support a HACCP-based food safety management system (Sperber et al., 1998). Numerous studies have evaluated the factors associated with the implementation and impact of FSMS on food hygiene standards and food safety knowledge and practices. For example, legally mandating a FSMS in food establishments has been shown to improve food hygiene standards (Djekic et al., 2016). FSMS-implementing food establishments in

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several European cities were reported to have significantly higher food hygiene rating (Djekic et al., 2014). In China, the implementation of HACCP-based FSMS in small and/or less developed food businesses was associated with increased levels of food handlers' hygiene practices and food safety knowledge (Yang, Wei, & Pei, 2019). Restaurants assessed to have a higher risk of foodborne disease implemented FSMS more poorly compared to those with a lower risk of foodborne disease (de Andrade, Stedefeldt, Zanin, & da Cunha, 2020). The effective implementation of FSMS in food businesses has been reported to be hindered by poor documentation and record keeping, inaccurate hazard assessments, overly-simplified or -complex process flow diagrams and the absence of management systems validation and verification (Dzwolak, 2019). Although the uptake of FSMS has grown considerably across the globe (Gil, Ruiz, Escrivá, Font, & Manyes, 2017), evidence demonstrating the impact of FSMS implementation specifically on foodborne disease reduction and regulatory compliance is limited.

An interrupted time-series analysis can be used to evaluate the impact of an intervention through a quasi-experimental research design (Kontopantelis, Doran, Springate, Buchan, & Reeves, 2015) and is a powerful approach in evaluating the longitudinal impact of policy interventions (Wagner, Soumerai, Zhang, & Ross-Degnan, 2002). This study design involves the construction of a time series of the outcome measure and compares the trend before and after the introduction of the intervention being evaluated. The appropriate use of a control group within such a study design helps to account for the effect of secular trends on the outcome trajectory. The interrupted time-series analytical approach has been used to evaluate the impact of policies aimed at improving food safety and reducing diarrhoeal disease. Examples of such policy evaluations include the impact of a national raw beef liver consumption ban in restaurants on Enterohemorrhagic *Escherichia coli* infections in Japan (Iwata & Goto, 2019) and the impact of publicly displayed restaurant inspection letter grades on *Salmonella* infections in New York, USA (Firestone & Hedberg, 2018).

In June 2014, the National Environment Agency (NEA) in Singapore mandated the implementation of FSMS in all NEA-licenced food catering service establishments to improve food safety. However, its impact on public health outcomes has yet to be evaluated. In this study, we investigated the effects of FSMS implementation on foodborne disease outbreaks and reported food hygiene violations associated with food catering service establishments in Singapore using a controlled interrupted time-series analysis.

2. Materials and methods

2.1. Study area

In the city-state of Singapore, food establishment operators must obtain a licence from the NEA before they can operate. In 2018, there were approximately 39,000 NEA-licenced food establishments in Singapore (Ministry of Environment and Water Resources, 2019). Of these, almost 400 were specifically licenced as food catering service establishments. Public health inspectors from the NEA carry out periodic health inspections of all retail food establishments with the aim of ensuring high standards of food hygiene standards. Financial penalties may be imposed for reported food hygiene violations. [Note: The Singapore Food Agency (SFA) was formed in April 2019 and all food safety functions were permanently transferred from the NEA to the SFA].

2.2. Outcome measures

We analysed two outcome measures associated with licensed food catering service establishments at the national level: (i) foodborne outbreak notifications, and (ii) reported food hygiene violations.

2.2.1. Foodborne outbreak notifications

A case of food poisoning was defined as an individual who, after consumption of a specific meal, experiences either two or more of the following symptoms: nausea, vomiting, diarrhoea, abdominal pain, fever; or several bouts of vomiting or diarrhoea alone. A notified foodborne outbreak was defined as two or more reported cases of food poisoning linked in space and time through epidemiological investigation carried out jointly by the Ministry of Health (Singapore) and the NEA. All outbreak notifications that were linked to licenced retail food establishments were consolidated at the NEA. Based on the type of food establishment implicated, the NEA then classified the outbreak as linked to a catering food service establishment or a non-catering food establishment. We obtained from the NEA monthly reports of notified foodborne outbreaks linked to food catering service and non-catering food establishments from January 2012 to December 2018.

2.2.2. Reported food hygiene violations

Under the Environmental Public Health (Food Hygiene) Regulations administered by the NEA, there were 115 unique violations listed for food establishments. We examined the list and classified 72 violations as those directly related to food hygiene (see Appendix A. Supplementary data Table A.1). The majority of the remaining were related to the compliance of the NEA's administrative requirements for such establishments. In our study, we defined a reported food hygiene violation as any of the 72 violations detected during a regulatory inspection of a NEA-licenced food establishment. We obtained from the NEA monthly reports of food hygiene violations in all licenced retail food establishments that occurred between June 2012 and December 2018.

2.3. FSMS intervention

In our study, the FSMS was the intervention of interest. From June 2014, all NEA-licenced food catering service establishments in Singapore were legally required to establish a HACCP-based FSMS, its corresponding prerequisite programmes and a documentary system to record their FSMS development and implementation (SPRING Singapore, 2013, p. 2013). Food catering service establishments licenced before June 2014 were given a grace period of 12 months to implement FSMS while those licenced after June 2014 had to do so before they start food production operations.

In food production, a critical control point (CCP) is a step, process or procedure where the application of a control measure will either eliminate or reduce a food hazard to an acceptable level. As part of the mandatory legal requirements of FSMS implementation in Singapore, food catering service establishment operators were required to submit an FSMS plan that included a flow diagram of their food production process with identified CCPs. In addition, operators were required to monitor and document the critical limits for the CCPs, including the corrective actions taken during the exceedance of those critical limits. During routine FSMS compliance inspections, food operators were required to produce documentary records of their monitoring and corrective actions to demonstrate legal compliance to visiting public health inspectors. There was however, no mandatory requirement for the upkeep of records pertaining to the implementation and adherence to prerequisite programmes.

2.4. Statistical analysis

We used a controlled interrupted time-series analytical study design to evaluate the impact of FSMS on our two study outcome measures. We analysed the data on a monthly timescale to evaluate the effects of the FSMS intervention. We estimated the change in the average level of foodborne outbreak notifications and food hygiene violations in food catering service establishments following its introduction, and compared the pre- and post-intervention trends using Poisson regression while adjusting for potential confounders such as the rate of the outcome in the control group, serial correlation and seasonal patterns of

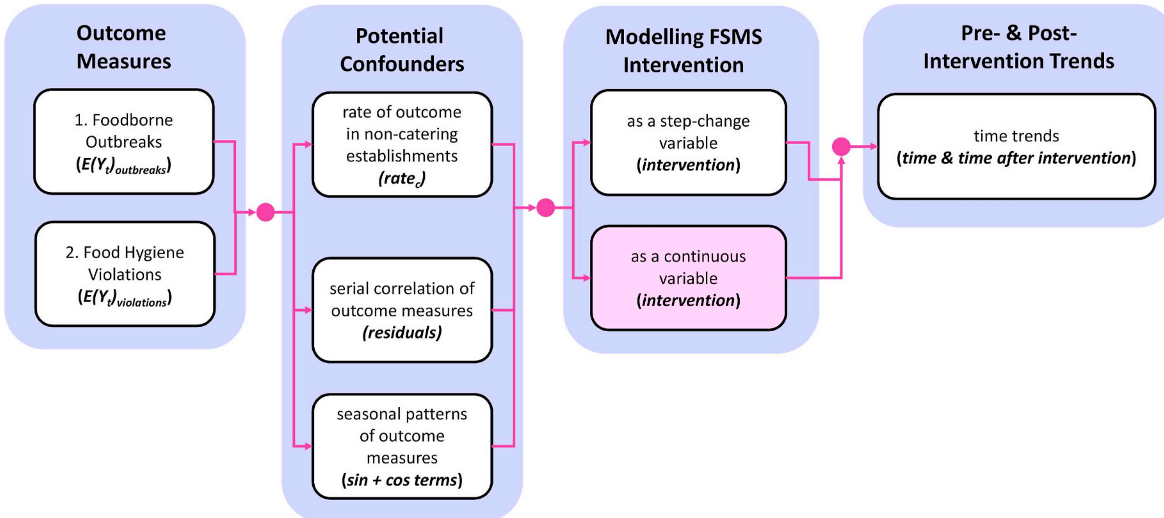

Fig. 1. Analytical approach for modelling impact of FSMS. The shapes with white background depict the main analysis while the shape with the pink background depicts the sensitivity analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the outcome (see Fig. 1). To help illustrate how time series data might look before and after an intervention, we illustrate hypothetical examples in Fig. 2.

Similar to other studies (Livingston, Barnett, Delcher, & Wagenaar, 2017; McKee et al., 2017), we included the outcome measure of the comparison group (non-catering food establishments) as a covariate in the model to directly control for secular trends. We expected to observe evidence of any impact after the grace period. However, FSMS uptake did not reach its peak until December 2015. Using a step-change variable, we estimated the impact of FSMS at its maximum uptake over the last 37 months of the study period. In order to capture the effects of FSMS during the grace period, we undertook sensitivity analysis using a continuous variable to account for the high variability in FSMS uptake in its initial 18 months of implementation in order to estimate the impact in the 55-month post intervention period (18 + 37 months).

We assessed the seasonality of each outcome measure using periodic sine and cosine terms with a likelihood ratio test (LRT). Autocorrelation of the outcome measure, which measures the relationship between its present and lagged values, may potentially influence the significance of results. We examined the Autocorrelation Functions (ACF) and Partial Autocorrelation Functions (PACF) from our final models and adjusted for any remaining autocorrelation using deviance residuals (Brumback et al., 2000). We examined the impacts of FSMS on foodborne outbreaks using equation (1) and on food hygiene violations using equation (2):

$$E(Y_t)_{outbreaks} = \beta_0 + \beta_1 time + \beta_2 intervention + \beta_3 time\ after\ intervention + \beta_4 rate_c + \log(population) \quad (1)$$

$$E(Y_t)_{violations} = \beta_0 + \beta_1 time + \beta_2 intervention + \beta_3 time\ after\ intervention + \beta_4 rate_c + \log(population) + \sum_{k=3}\left[\beta_5 \sin\left({}^{2\pi kt}/_{12}\right) + \beta_6 \cos\left({}^{2\pi kt}/_{12}\right)\right] + \beta_7 residuals_{i=7} \quad (2)$$

where $E(Y_t)_{outbreaks}$ is the expected number of food poisoning outbreaks and $E(Y_t)_{violations}$ is the expected number of reported food hygiene violations associated with food catering service establishments at month t, *time* is the monthly time variable and represents the number of months elapsed since the beginning of the study period, *intervention* represents the full impact of the FSMS intervention when its uptake was sustained (when modelled as a step-change variable it is coded "0" before December 2015 and "1" thereafter; when modelled as a continuous variable it takes on values of the FSMS uptake rate), *time after intervention* represents the number of months elapsed after the FSMS term takes on non-zero values (when the FSMS is modelled as a step-change variable, it is coded "0" before December 2015 and increases by 1 per month till the end of the study period; when the FSMS is modelled as a continuous variable, it takes on the monthly values of the FSMS uptake rate), *log*

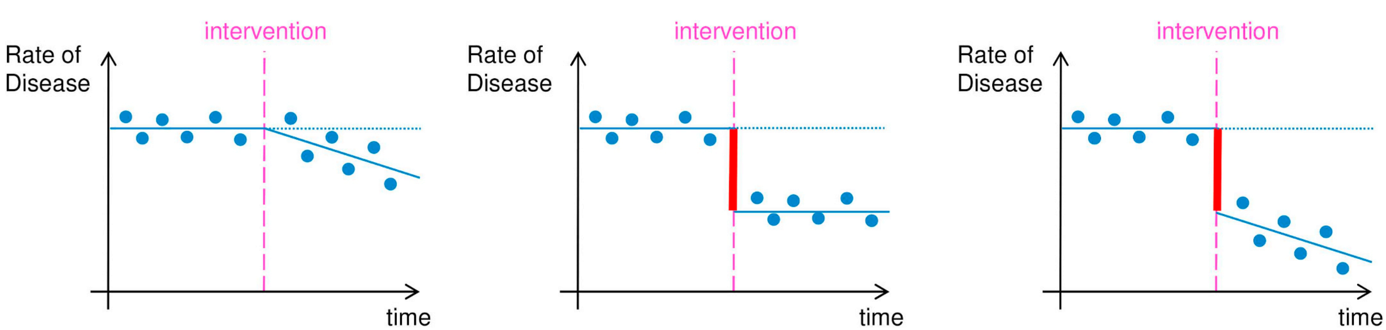

Fig. 2. Hypothetical examples of interrupted time series analysis of policy interventions aimed at reducing foodborne disease. The pink vertical dashed lines distinguish the pre- and post-intervention periods, the solid blue circles represent the hypothetical observed rates of disease and the solid blue lines indicate the modelled trend of disease. The dotted blue line represents the pre-intervention disease trend while the vertical red line represents a drop in the average level of disease. In panel [A], there is a decline in the trend of foodborne disease following the intervention but no change in the average level of disease. In panel [B], there is no change in the trend of foodborne disease following the intervention but there is a decrease in the average level of disease. In panel [C], there is both a decline in the trend and a drop in the average level of disease following the intervention. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(population) refers to the offset variable to account for the monthly number of food establishments in equation (1) and the monthly number of regulatory inspections in equation (2), $rate_c$ refers to the rate of the outcome measure in non-catering food establishments at month t, the *sin* and *cos* terms capture the within-year periodic fluctuations in the outcome measure and *residuals* refer to the deviance residuals used to account for autocorrelation. β_0 is the model intercept and the starting level of the outcome variable for food catering service establishments, while the remaining β coefficients represent the strength of the respective independent relationships with the outcome measure (see Appendix A. Supplementary data Tables A.2a and A.2b for examples of the matrix setup). More detailed guidance on the use of interrupted time-series study designs are described elsewhere (Lagarde, 2012; Lopez Bernal, Cummins, & Gasparrini, 2016).

We expressed the measure of effect for each independent term in the final model as an incidence rate ratio (IRR); that is the change in the proportion of the outcome measure (referencing the mean), associated with each unit change in the corresponding independent term. The IRR for each independent variable is computed by exponentiating its β coefficient. We used Akaike's Information Criterion to aid model selection (Akaike, 1974). We evaluated statistical significance at the 5% level. We performed all analyses using STATA 12.1 software (StataCorp, USA). Ethics approval for this study was granted by the University of New South Wales Human Research Ethics Committee (HC17218).

3. Results

3.1. Descriptive analysis

3.1.1. FSMS uptake rate

Upon its introduction, the uptake of FSMS increased by an average of 4.1% per month from June 2014 to November 2015 (18 months), after which it plateaued at an average of 93.8% from December 2015 to December 2018 (37 months).

3.1.2. Foodborne outbreak notifications

There were 42 foodborne outbreak notifications linked to food catering service establishments and 754 linked to non-catering food establishments. The overall rates of outbreak notifications were 1.36 per 1000 catering establishments and 0.23 per 1000 non-catering establishments. Rates of notifications in catering establishments were not significantly lower when comparing pre- and post-intervention periods while those in non-catering establishment were significantly higher ($p = 0.004$) in the post-compared to the pre-intervention period (see Table 1). The FSMS uptake rate reached its peak in December 2015 (see Fig. 2).

3.1.3. Food hygiene violations

Over the study period there were 521 reported food hygiene violations and 9484 health inspections among food catering service establishments and 13,730 food hygiene violations and 830,690 health inspections among non-catering food establishments. The overall rates of reported violations were 56.60 per 1000 catering establishments and 18.13 per 1000 non-catering establishments. Rates of violations in non-catering establishments were significantly higher ($p < 0.001$) in the post-compared to the pre-intervention period (Table 1). The majority of the twenty most common violations related to aspects of food production were usually addressed by prerequisite programmes (see Appendix A. Supplementary data Table A.3). The top three violations were the same in both groups of food establishments, and these were: (i) Failure to keep the licenced premises clean, (ii) failure to keep the licenced premises free of infestation and (iii) failure to register food handlers. The twenty most frequent types of hygiene violations among food catering service establishments accounted for 93.7% of the total violation counts in that group. The corresponding violations among non-catering food establishments accounted for 95.6% of the total violation counts in that group. The rate of food hygiene violations among food catering service establishments appeared to be highly variable throughout the study duration, with a slight upward trend after the introduction of the FSMS (see Fig. 3). The trend of the monthly rate of violations among non-catering food establishments appeared to be relatively stable until 2017 where there was a slight upward trend.

Table 1
Average reported rates of foodborne outbreaks and food hygiene violations associated with NEA-licensed food establishments in Singapore, 2012 to 2018.

Categories of Food Establishments	Reported Rates Per 1000 Food Establishments					
	Foodborne Outbreaks			Food Hygiene Violations		
	Pre-FSMS	Post-FSMS	*t*-test p-value	Pre-FSMS	Post-FSMS	*t*-test p-value
Food catering	1.65	0.99	0.195	55.75	57.57	0.807
Non-food catering	0.18	0.30	0.004	13.32	23.61	<0.001

3.2. Multivariable regression analysis

3.2.1. The effect of FSMS on foodborne disease outbreaks associated with food catering services

In our first model (1a) assessing the impact of FSMS that excluded the grace period and early period of implementation, we observed a 78.4% (IRR: 0.216, 95% CI: 0.050 to 0.940, $p = 0.041$) reduction in the average level of foodborne outbreaks from December 2015 to December 2018 (Table 2). In our second model (1b) capturing the effects of FSMS in the grace period and the early phase of implementation, we observed a non-significant 65.1% decrease (IRR: 0.349, 95% CI: 0.053 to 2.302, $p = 0.274$) in the average level of foodborne outbreaks from June 2014 to December 2018 (see Fig. 4). During the grace period and the early phase of implementation, every 10% increase in uptake was associated with a 10.6% non-significant decrease (IRR: 0.894, 95% CI: 0.731 to 1.093, $p = 0.274$) in the average level of foodborne disease outbreaks.

The rate of outbreak notifications in non-catering food establishments was non-significant in both models (see Table 2), indicating that there was no evidence of changes in the secular trend. The lower AIC value for the step-change model indicated better model fit compared to that of the continuous-change model. There was no residual autocorrelation of foodborne outbreak notifications in the final best fitting model (1a) (see Appendix A. Supplementary data Table A.4 and Fig. A.1).

3.2.2. The effect of FSMS on food hygiene violations associated with food catering services

After controlling for the potential confounding effects of secular trends, the seasonality of food hygiene violations and autocorrelation (see Appendix A. Supplementary data Table A.5 and Fig. A.2), we found no evidence of a significant effect of FSMS on the average rate of reported food hygiene violations regardless of how we modelled the intervention (see Table 3). In the step-change model (2a), there was a non-significant 23.3% (IRR: 0.767, 95% CI: 0.542 to 1.087, $p = 0.136$) reduction in food hygiene violations in the final 37 months of our study. When we assumed a constant uptake of 93.8% over the entire period 55-month period (which includes the initial 18-month grace period and the final 37 months of FSMS implementation) in model (2b), we observed a non-significant 3.7% decrease (IRR: 0.963, 95% CI: 0.582 to 1.594, $p = 0.885$) in the average level of food hygiene violations from June 2014 to December 2018. The AIC value for the continuous-change model (2b) was lower than that of the step-change model (2a) indicating that the former was a better fit.

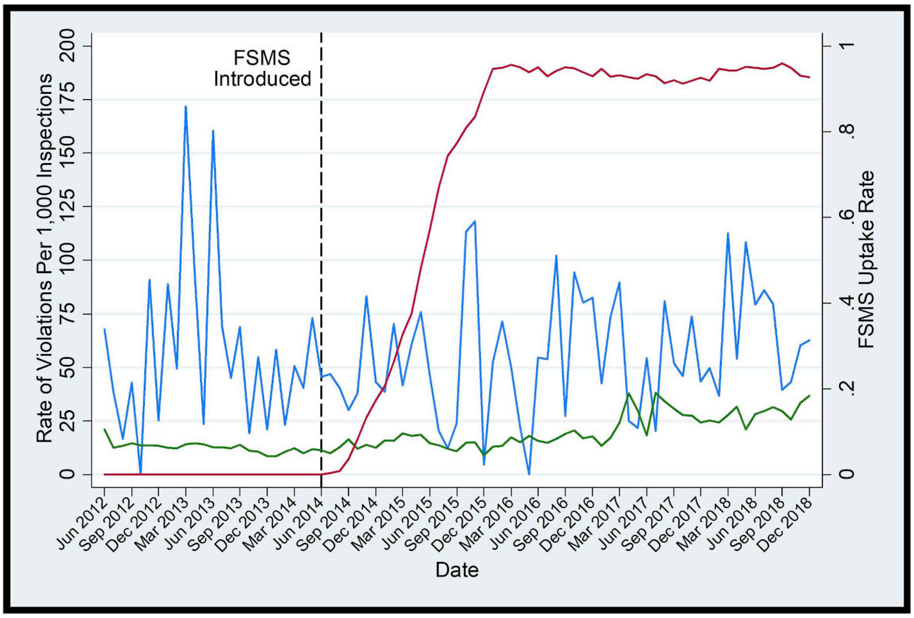

Fig. 3. Monthly rate of reported food hygiene violations in NEA-licenced food catering service establishments and non-catering food establishments in Singapore, June 2012 to December 2018. The solid blue line represents the monthly rate trend of reported food hygiene violations in food catering establishments, while the solid green line represents the monthly rate trend of food hygiene violations in non-catering food establishments and the solid brown line represents the monthly FSMS uptake rate. The vertical black dashed line indicates the month that FSMS was introduced. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

A major benefit of the increased uptake of FSMS across the globe in the last decade has been the marked improvement in the quality and safety of food production (Gil et al., 2017). Previous systematic reviews have reported on the effectiveness of various public health interventions aimed at improving food safety outcomes such as inspection scores, food hygiene violations, food handler knowledge and performance, management practices and microbial quality of food (Campbell et al., 1998; Viator, Blitstein, Brophy, & Fraser, 2015). However, few studies have examined the epidemiological impact of FSMS uptake on foodborne disease transmission and regulatory compliance with food hygiene standards.

In this study, we evaluated the effect of the legally mandated FSMS intervention in food catering service establishments in Singapore. We observed a reduction in foodborne disease outbreaks associated with the FSMS intervention. This reduction was statistically significant and occurred 18 months after the introduction of FSMS. As there were no changes in the reporting requirements for outbreaks, nor any change in food safety policies, nor an observable change in secular trends reflected by non-food catering service establishments, it seems reasonable to attribute the observed reduction to the widespread implementation of FSMS over a sustained period. This finding was consistent with studies that reported the positive impact of public health interventions on foodborne disease (Ashley, Walters, Dockery-Brown, McNab, & Ashley, 2006; Firestone & Hedberg, 2018; Pollari et al., 2017).

When we included the effects of FSMS in the first 18 months of its implementation, we observed a less pronounced and statistically non-significant overall reduction in food catering service related foodborne outbreaks. This suggests that the early phase of FSMS implementation may have had less influence on foodborne outbreaks. This could be due to the low uptake during the 12-month grace period – FSMS uptake among legally obligated establishments was lower than 50% during the first 12 months of implementation. Poor adherence to improved food hygiene rules linked to the initial period of FSMS implementation may also nullified food safety improvements that would have benefitted from effective FSMS implementation. A previous survey carried out in the UK reported that 17% of food establishments which had implemented FSMS for more than 1.5 years, had yet to do so fully (Jigsaw Research, 2007). A study assessing food safety systems implementation in children's nurseries over a 11-year period reported that while documentation compliance reached high levels, food safety practice compliance was comparatively much lower because of poor implementation of hygiene rules by staff (Trafialek, Domańska, & Kolanowski, 2019).

In our study, we did not observe any evidence of a reduction in reported food hygiene violations in food catering establishments following the implementation of the FSMS intervention. This was inconsistent with other studies that reported improvements in food safety

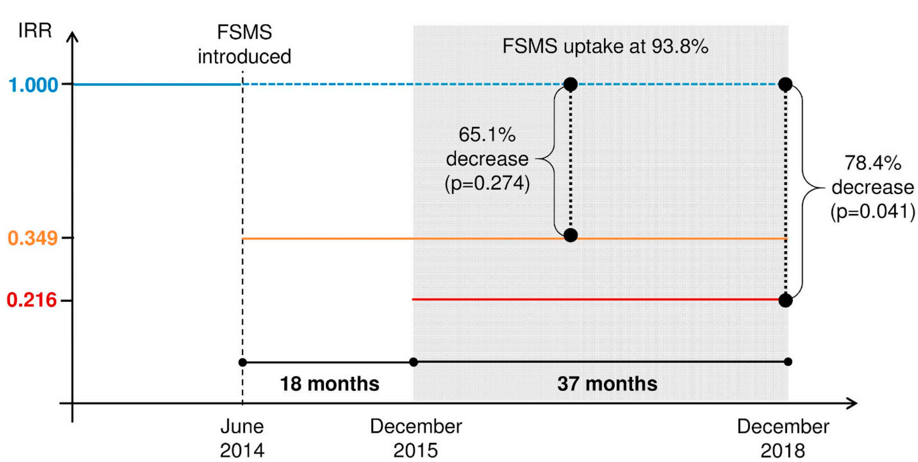

Fig. 4. The impact of FSMS on catering food service establishment-related foodborne disease outbreaks in Singapore, 2012 to 2018. The solid blue line depicts the mean baseline rate of outbreaks before the implementation of FSMS. The dotted blue line represents the counterfactual, which is the expected mean baseline rate in the absence of any intervention. The solid orange line depicts the FSMS effect taking into account the grace period and early phase of implementation while the solid red line depicts the FSMS effect when its uptake stabilized at an average level of 93.8%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
The adjusted impact of FSMS on foodborne outbreak notification trends in food catering establishments in Singapore, January 2012 to December 2018.

Variables	IRR	95% CI		p-value (Wald Test)	AIC Value
Model 1a - Impact of FSMS over final 37-month *period (step-change model)*					2.04
Baseline trend	1.019	0.987	1.051	0.247	
Average level change from December 2015	0.216	0.050	0.940	0.041	
Post intervention trend	1.026	0.967	1.089	0.399	
Foodborne outbreak notification rate of non-catering food establishments	1.712	0.212	13.800	0.614	
Model 1b - Impact of FSMS incorporating early phase of adoption (continuous-change model)					2.08
Baseline trend	1.019	0.972	1.069	0.434	
Average level change for every 10% increase in FSMS uptake	0.894	0.731	1.093	0.274	
Post intervention trend	1.014	0.964	1.066	0.598	
Foodborne outbreak notification rate of non-catering food establishments	1.029	0.132	8.036	0.979	

following FSMS implementation. Legally mandating a HACCP based FSMS in food establishments has been shown to improve food hygiene standards (Djekic et al., 2016). In a multi-city study on food hygiene practices in Europe, food establishments which implemented the HACCP-based food safety management system were associated with a significantly higher food hygiene rating (Djekic et al., 2014).

There are two possible explanations for the lack of an observed association between FSMS implementation and reported food hygiene violations. Firstly, although some of the most common hygiene violations considered in our analysis related to the critical control points for food production, the majority of the top violations pertained to other facets of food production that are usually addressed by the judicious adherence to prerequisite programmes (which are an essential component of the FSMS). Poor implementation of FSMS prerequisite programmes in some food businesses may have contributed to the sustained trend of reported violations throughout the study duration. Greater focus of regulatory FSMS compliance inspections on CCPs and their monitoring and corrective activities may potentially have drawn an important part of food operators' emphasis and resources away from ensuring effective implementation of prerequisite programmes. Secondly, the post-FSMS implementation study duration may not have been long enough to detect statistically significant effects on reported violations. Although our finding was non-significant ($p = 0.134$), we did observe that reported food hygiene violations in catering food service establishments reduced by almost a quarter after FSMS implementation. Future studies analysing the effect over a longer study duration may be able to establish with greater certainty the impact of FSMS on reported violations.

While the reported food hygiene violations may represent threats to the standards of food hygiene surrounding the food production process, CCPs must fail to address their impact in order for these food safety lapses to increase the risk of foodborne disease transmission. Judicious application of control measures at the identified CCPs may have addressed the additional risk posed by observed food safety lapses, resulting in improved epidemiological outcomes. This would be consistent with an observed reduction in outbreak notifications in food catering establishments but not a parallel reduction in reported food hygiene violations. However, this does not mean that there is no utility in reporting such violations. In fact, these violations provide clues on the effectiveness of executing prerequisite programmes, which are an important part of any FSMS.

The ability of a FSMS to help prevent foodborne disease is dependent on its correct application (Motarjemi & Käferstein, 1999). Analysing retrospective foodborne disease outbreak data and communicating the findings can improve the review and implementation of FSMS in food businesses (Panisello, Rooney, Quantick, & Stanwell-Smith, 2000). It may be useful for the national food safety agency in Singapore to review implementation of prerequisite programmes in FSMS-certified establishments, especially in those that were implicated in foodborne outbreaks in the post-intervention period. As findings of regulatory inspectors and establishment based self-audits have been reported to differ (Turku, Lepistö, & Lundén, 2018) and knowledge of foodborne disease may differ by the field of education (Al-Mohaithef et al., 2020), reinforcing the importance of food production safety among food production managers and food handlers may increase the effectiveness of FSMS implementation. Reinforcing food handler education has been demonstrated to improve food microbial safety (Gomes, Lemos, Silva, Hora, & Cruz, 2014) and microbial assessment can provide important insights into the effectiveness of FSMS (Njage et al., 2017). The national food safety agency may also wish to consider the

Table 3
The adjusted impact of FSMS on food hygiene violation rate trends in catering and non-catering retail food establishments in Singapore, June 2012 to December 2018.

Variables	IRR/Coefficients[+]	95% CI		p-value (Wald Test)	AIC Value
Model 2a. Impact of FSMS over final 37-month *period (step-change model)*					5.57
Baseline trend	1.000				
Average level change from December-2015	0.767	0.542	1.087	0.136	
Post intervention trend	1.012	0.995	1.030	0.164	
Violation rate of non-catering food establishments	1.004	0.981	1.027	0.759	
Sine function (4-monthly)	0.094[+]	−0.029	0.216	0.133	
Cosine function (4-monthly)	−0.142[+]	−0.266	−0.019	0.024	
Model 2b. Impact of FSMS incorporating early phase of adoption (continuous-change model)					5.39
Baseline trend	0.958	0.936	0.981	< 0.001	
Average level change For every 10% increase in FSMS uptake	0.996	0.944	1.051	0.885	
Post intervention trend	1.008	0.990	1.025	0.386	
Violation rate of non-catering food establishments	1.003	0.979	1.029	0.784	
Sine function (4-monthly)	0.091[+]	−0.040	0.221	0.173	
Cosine function (4-monthly)	−0.170[+]	−0.297	−0.043	0.009	

[+] Only beta coefficients shown for periodic functions; IRRs not shown due to non-linearity.

use of microbiological indicators in assessing effective FSMS implementation among food catering service establishments implicated in foodborne outbreaks in Singapore.

Our study provides evidence to suggest that the legally mandated FSMS implementation is an effective food safety policy to reduce the risks of foodborne outbreaks associated with food catering services. This evidence supports the rationale for mandatory FSMS implementation not just in other categories of high risk food establishments in Singapore but also in similar cosmopolitan cities around the world. Given the substantial resources required to implement and sustain FSMS in food production, the expansion of FSMS implementation to different categories and sizes of food establishments must be tailored in order to maximize its effectiveness. Future studies evaluating the impact of FSMS expansion on food safety measures should be undertaken to ensure that they are effective in reducing food safety lapses and foodborne disease.

4.1. Strengths and limitations

We utilised well-defined outcome measures extracted from the comprehensive regulatory inspection and foodborne outbreak notification national-level databases of the NEA. We included all notifications and violations in our analysis and therefore our study results are generalizable at the national level. We were able to control for the impact of secular effects on the outcome measures by adjusting for the pattern in a control group that would most likely be subject to the same external influences. Reports of foodborne outbreaks linked to food establishments likely reflected those where food poisoning symptoms in affected individuals were severe enough to warrant public feedback to the health authorities that triggered the outbreak investigations. These are however likely to exclude episodes of milder food poisoning symptoms that go unreported and are thus not investigated. Our study may thus under represent the true number of foodborne outbreaks in the community. However, there is no reason to believe that the underreporting rates would differ over time between food catering and non-catering food establishments. Self-directed improvements made by food businesses not related to the intervention could have strengthened our effect estimates for FSMS. Future studies analysing the effects of FSMS at the individual food business-level may obtain more accurate effect estimates.

5. Conclusions

Our study found that the legally mandated FSMS intervention in food catering service establishments was associated with a delayed but significant reduction in foodborne disease outbreaks. Health authorities seeking to reduce outbreaks in food catering operations should consider mandating FSMS. We found that food hygiene violations did not change after the intervention, which may indicate that they are a poor predictor of the risk of outbreaks.

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CRediT authorship contribution statement

Joel Aik: Conceptualization, Data curation, Formal analysis, Methodology, Writing - original draft. **Anthony T. Newall:** Conceptualization, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

All authors declare that they have no conflict of interests.

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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.2020.107324.

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