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Multi-criteria decision analysis to evaluate control strategies for preventing cross-contamination during fresh-cut lettuce washing

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ABSTRACT

Several chemical disinfection strategies may be used to control cross-contamination of pathogens during fresh-cut produce washing. Deciding which strategy to select not only requires the use of technical information on the relevant criteria but can also make use of stakeholder perception. This study aimed to describe the application of a Multi-Criteria Decision Analysis (MCDA) to support decision-makers when determining a control strategy that best meets the views of various stakeholders and their possible conflicting interests. In this case study, five control strategies that can be used to treat the wash water, which comes in direct contact with the produce in the wash tank during processing, were examined. These strategies aimed to control pathogenic cross-contamination during fresh-cut lettuce washing at processors. These strategies included the use of free chlorine, chlorine dioxide, ozone, peracetic acid, or no wash water disinfectant. The performance analysis was based on five main criteria: Effectiveness, Technological aspects, Consumer acceptance, Economics, and Health. Scores for these criteria were evaluated using scientific literature, while the weights of the criteria were assessed using stakeholders. Results for the five control strategies were determined per stakeholder group, which included fresh-cut processors, producers and suppliers of disinfectants and equipment, scientists, and government representatives, as well as per individual. Stakeholders were shown to have different views on the relative importance of the criteria; however, the criterion “Health” was consistently considered most important. The ranking of the control strategies was similar for each stakeholder group and over stakeholders. Overall, the results showed that peracetic acid is the preferred control strategy. Based on the results of these analyses, the MCDA approach may assist in the complex decision to select a control strategy to control potential cross-contamination directly in the wash tank during fresh-cut lettuce washing by considering the different nature of the criteria and the perceptions of various stakeholder groups.

1. Introduction

A report from the European Food Safety Authority (EFSA) has ranked the risk of foodborne disease resulting from pathogens in foods of non-animal origin (FoNAO) and provides insight into likely pathogen-food combinations of concern to human health (EFSA Panel on Biological Hazards (BIOHAZ) (2013). For FoNAO where the edible portion is intended to be eaten uncooked, like that of fresh-cut lettuce, both contamination and cross-contamination should be controlled. This control is essential as, throughout the different stages of the food chain, there is no pathogenic reduction, except a minimal effect during washing. An effective way to prevent contamination and cross-contamination is to disinfect the wash water. In order to clean the lettuce, washing with water helps remove dirt, soil, sand, and any physical contamination that may occur. If the wash water used is contaminated, it can become a source of contamination for uncontaminated parts (Allende, Selma, Lopez-Galvez, Villaescusa, & Gil, 2008; Banach et al., 2017; Holvoet, Jacxsens, Sampers, & Uyttendaele, 2012). Therefore, disinfecting the wash water can be considered necessary. Using chemical disinfectants, like free chlorine or peracetic acid, directly in the washing tank has been shown to be effective. However, doing so can cause the formation of disinfection by-products (DBPs) in the washing water (Banach, Sampers, Van Haute, & van der Fels-Klerx, 2015; Van Haute, Sampers, Holvoet, & Uyttendaele, 2013). Control

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measures should aim to prevent (cross-) contamination of pathogens without jeopardizing chemical safety. Hence, both microbiological and chemical food safety needs to be ensured.

The type of disinfectant products that can be used during fresh-cut produce washing can vary in the European Union (EU) between member states. Ultimately, it is the member states who are responsible for the final evaluation and authorization of the use of disinfectant products (or biocidal products) before they are placed on the market. While controlling the water used during fresh-cut lettuce processing, several complex or conflicting criteria may need to be considered before deciding how to mitigate food safety risks that affect human health. The ability for stakeholders, including policymakers, to make an informed decision and set future policies to implement, or to take corrective actions, becomes multifaceted and, therefore, complicated. However, there are tools available to help facilitate the decision-making process. Van der Fels-Klerx et al. (2018) reviewed methods to rank the risk to human health of food-related hazards; among these is a decision-making tool known as a multi-criteria decision analysis (MCDA).

Stakeholders are parties with interest in the decision to be made, and involving them in the decision-making process on the selection of control strategies may increase the uptake and the optimal allocation of resources towards the strategy. Moreover, their involvement can increase the balance in the decision. A decision may not be optimal for one stakeholder, but it is one that includes the interest of different stakeholders, which creates support for the decision selected. By using an MCDA, stakeholders can rank the relative importance of multiple diverse, complex, or even conflicting criteria associated with a case. An MCDA aims to help decision-makers select the best scenario(s) based on several criteria, including criteria that have qualitative or (semi-) quantitative data and may be conflicting between the stakeholders. It can be used to combine different types of knowledge or non-comparable outcomes, such as economic impact and health impact (Van der Fels-Klerx et al., 2018). Often, an MCDA can be useful if there is no clear "optimal" solution, yet where the various criteria need to be prioritized among one another to try to find the best compromise (Duret et al., 2019). Overall, an MCDA is a tool that facilitates policy and decision-makers in selecting alternatives and making decisions by providing a comparison of the potential choices and brings structure to the decision-making process.

In the field of food safety, the MCDA approach has been used in the scientific community and by international organizations like the World Health Organization (WHO). For instance, in recent years, the WHO used an MCDA to globally rank foodborne parasites using qualitatively assessed criteria (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 2014). Also, Ruzante, Grieger, Woodward, Lambertini, and Kowalcyk (2017) outlined an MCDA approach to conduct a food safety risk-benefit assessment to select interventions (i.e., control strategies) for controlling pathogens in foodstuffs. In another study, Duret et al. (2019) further evaluated the MCDA approach while focusing on the cold chain of cooked ham to predict the risk for human health associated with *Listeria monocytogenes*. In general, the MCDA approach regularly focuses on ranking possible food safety hazards and risks and less frequently has evaluated potential control strategies (Dunn, 2015).

When selecting a control strategy to prevent cross-contamination during fresh-cut produce washing, several criteria such as effectiveness, the technology used, consumer acceptance, economics, and public health may be considered. The objective of this study was to explore the use of an MCDA to select the best control strategy to treat the wash water used directly in the wash tank during fresh-cut lettuce washing to control cross-contamination with pathogens.

2. Materials and methods

2.1. Decision problem

Several chemical-based technologies are available to disinfect the water used during fresh-cut lettuce processing. Among others, the review of Banach et al. (2015) reported that free chlorine, chlorine dioxide, ozone, and peracetic acid could be effective process wash water disinfectants to reduce cross-contamination of pathogens during produce washing. In some European countries, like in the Netherlands, the use of chemical-based wash water disinfectants is currently not applied during fresh-cut processing. Therefore, the use of these four technologies against the current alternative option – no wash water disinfectant – is of interest to assess. Several peer-reviewed scientific literature sources were used to determine the performance scores of the strategies (section 2.3).

Four groups of stakeholders were considered relevant for our case study, including (i) fresh-cut processors, (ii) producers and suppliers of disinfectants and equipment, (iii) scientists, and (iv) government representatives. The views of these four stakeholder groups were elicited using an online survey with a select set of questions (section 2.4) to determine the preference weights of the criteria considered to evaluate the control strategies.

2.2. Case study and criteria

The following case study with assumptions was defined at the start of the study to ensure that survey respondents had the same conditions in mind when filling in the survey: "A fresh-cut lettuce processor treats the wash water directly, i.e., in the wash tank, using one of the five strategies: (i) free chlorine, (ii), chlorine dioxide, (iii) ozone, (iv) peracetic acid, or (v) no disinfectant. The strategy is applied directly to a single commercial wash tank (3.5 m^3), which processes 800 kg of freshly cut lettuce in 90 min (which equates to one run). Processing is performed six days a week, with four runs per day, over five years. The processing equipment, including the wash tank, is cleaned in between each run. Furthermore, the technology is automated, i.e., an automated dosing system is used to treat the wash water. The consumer price of the (packed) lettuce is not supposed to be affected by the application of chemical disinfection."

Five main criteria were identified to be relevant to evaluate the control strategies: (i) Effectiveness, (ii) Technological aspects, (iii) Consumer acceptance, (iv) Economics, and (v) Health. Similar criteria have been used in other food safety MCDAs like effectiveness, practicality associated with the intervention (e.g., technology), and costs (e.g., economics) (Fazil, Rajic, Sanchez, & McEwen, 2008). The effectiveness of the control strategy is an important health aspect and is based on the potential microbial reduction in the water (i.e., $\log_{10}$ reduction in the water). In this case study, (i) Effectiveness was considered a pre-requisite for the control strategy. The preference weight was pre-determined at 20% for all stakeholder groups. All five control strategies, except "no use of a water disinfectant," were considered sufficiently effective. In total, nine sub-criteria were aggregated over the remaining four main criteria. For the main criterion (ii) Technological aspects, the three sub-criteria were how the technology could be applied in terms of its Ease of use, its Robustness, e.g., in terms of proper functionality over time, and the Scale of the technology, e.g., how much water can be treated with the technology. For the main criterion (iii) Consumer acceptance, the two sub-criteria were Consumer perception and Organoleptic effects. For the main criterion (iv) Economics, the two sub-criteria were the Costs for the producer, in terms of direct and indirect costs and which assumed a 5-year time for the technology, and Reduction in water use. Finally, for the main criterion (v) Health, the two sub-criteria were the additional unknown or adverse human health effects from the production of DBPs from the use of the technology, i.e., Possible side-effects and the adverse effects on Workers' safety. The main criteria and sub-criteria were grouped based on a previous list of impacts developed to address the specific nature of food safety policies and assessments of societal concern (Mazzocchi, Ragona, & Zanoli, 2013). Definitions of the sub-criteria (Appendix A) were based on expert input from scientists in the field of food safety and chemical engineering.

2.3. Performance scores of the control strategies

For the case study, qualitative scores were used to assess the performance of the five control strategies for each of the nine sub-criteria. These performance scores were based on the results from several peer-reviewed, comprehensive scientific literature reviews (Banach et al., 2015; Gil et al., 2009, 2015; Meireles, Giaouris, & Simões, 2016; Van Haute, Sampers, Jacxsens, & Uyttendaele, 2015). The scientific literature on the use of control strategies is shown in Table 1.

The scores were standardized to a value between 0 and 1, reflecting the worst to the best possible option, by dividing the score by the maximum obtained score per criterion. For the criteria where the highest point value was considered the worst possible option (e.g., Possible side-effects), one was subtracted from the score. Then, the performance scores of the sub-criteria were averaged per main criterion. Since the sub-criteria are averaged, these, in turn, become weighted.

2.4. Stakeholder survey

The online survey was developed to collect the stakeholders' views on the importance of the sub-criteria to consider before deciding which one of the five control strategies to apply. Respondents were asked to divide 100 points over the nine sub-criteria (see section 2.2 and Appendix A) and were asked not to use the same points for two or more of the criteria. The survey was sent by e-mail to a total of 36 stakeholders belonging to the four stakeholder groups. Respondents were guaranteed anonymity and were informed that the data were intended for scientific publication.

2.5. Calculate overall value

The performance scores, which were based on scientific literature, and the preference weights, which were based on the stakeholder inputs from the survey, were aggregated using a Weight Sum Model (WSM). A WSM is a transparent and straightforward model that is commonly used to rank alternatives based on the sum of the utility per indicator (Bartolini & Viaggi, 2010). According to Dunn (2015), in a WSM, a global performance score (*GP*) is determined based on the sum of the criterion performance scores (*p*) multiplied by the respective weights (*w*):

$$GP_i = \sum_{j=1}^{n} p_{ij} w_j$$

In the equation above, GP_i represents the global performance score associated with alternative *i* (i.e., one of the five control strategies in this case). The value p_{ij} represents the performance score of alternative *i* for criterion *j* (i.e., one of the five main criteria in this case), and w_j represents the weight allocated to criterion *j*. For each of the stakeholder groups, the global performance scores (*GP*) of the five control strategies were determined, given the performance scores (*p*) and the averaged weights of the respondents (*w*).

2.6. Scenario analyses

Since any of the five main criteria could affect the final ranking of the strategies, an alternative scenario was also examined. The scenario analysis was performed following the steps as earlier described, with one exception. The Possible side-effects for free chlorine were scored at 100 instead of 80, where 100 was the worst possible score. This change affected the averaged calculated standardized scores for chlorine

Table 1
Scores of the control strategy per criteria before standardization.

Control strategies	Criteria									
	Effectiveness	Technological aspects			Consumer acceptance		Economics		Health	
	Effectiveness (100 = max/best)	Ease of use (100 = max/easiest)	Robustness (5-point score = max/best)	Scale of the technology (5-point score = max/most water treated)	Consumer perception (100 = max/best)	Organoleptic effects (5-point score = max/worst)	Costs for producer (5-point score = max/worst)	Reduction in water use (5-point score = max/most)	Possible side-effects (100 = max/worst)	Workers' safety (5-point score = max/worst)
1. Use free chlorine[a]	100	70	2	3	30	1	1	3	80[b]	2
2. Use chlorine dioxide[c]	100	50	2	3	60	2	3	2	60	3
3. Use ozone[d]	100	50	3	1	60	3	3	2	30	4
4. Use peracetic acid[e]	100	70	2	2	60	2	2	1	30	1
5. Use no water disinfectant[f]	0	100	0	0	100	0	0	0	0	0

[a] Based on: Baert et al., 2009; Banach et al., 2015; Garrido et al., 2019; Gil & Allende, 2018; Gil et al., 2009; Gil et al., 2015; López-Gálvez, Allende, Selma, & Gil, 2009; López-Gálvez et al., 2010; Luo et al., 2011; Meireles et al., 2016; Tudela, Lopez-Galvez, Allende, & Gil, 2019; Tudela, Lopez-Galvez, Allende, Hernandez, et al., 2019; Van Haute et al., 2015.
[b] The score during the alternative scenario was 100.
[c] Based on: Banach et al., 2015; Banach et al., 2017; Banach, van Overbeek, Nierop Groot, van der Zouwen, & van der Fels-Klerx, 2018; Gil et al., 2009; López-Gálvez et al., 2010; Meireles et al., 2016; Petri, Rodríguez, & García, 2015; Van Haute et al., 2015.
[d] Based on: Ali, Yeoh, Forney, & Siddiqui, 2018; Banach et al., 2015; Chawla, Kasler, Sastry, & Yousef, 2012; Fang et al., 2014; Foong-Cunningham, Verkaar, & Swanson, 2012; Gil et al., 2009; Gil et al., 2015; Meireles et al., 2016; Papachristodoulou, Koukounaras, Siomos, Liakou, & Gerasopoulos, 2018; Selma, Allende, López-Gálvez, Conesa, & Gil, 2008; Van Haute et al., 2015.
[e] Based on: Baert et al., 2009; Banach et al., 2015; Banach et al., 2020; Davidson, Kaminski-Davidson, & Ryser, 2017; Gil et al., 2009; Gil et al., 2015; Meireles et al., 2016; Van Haute et al., 2015.
[f] Based on: Baert et al., 2009; Banach et al., 2017; Banach et al., 2020; Banach et al., 2018; Davidson et al., 2017; Gil & Allende, 2018; Gil et al., 2009; López-Gálvez et al., 2009; López-Gálvez et al., 2010; Papachristodoulou et al., 2018; Petri et al., 2015; Tudela, Lopez-Galvez, Allende, Hernandez, et al., 2019.

dioxide, ozone, and peracetic acid; however, the same weights per stakeholder were applied.

3. Results and discussion

3.1. Performance scores of the control strategies

Tables 1 and 2 list the performance scores of the original scenario before standardization and after standardization, respectively. When determining the original performance scores for the control strategy (Table 1), the input depended on the literature. Consequently, this interpretation and standardization are based on the assumptions made given the current literature and data available. The standardized performance scores of the sub-criteria (Table 2) were averaged per main criteria and are shown per control strategy (Table 3). The criterion "Effectiveness" was pre-set at either 1 or 0 for each strategy. The criterion "Technological aspects" ranged from 0.33 for the use of no water disinfectant to 0.79 for the use of free chlorine. The criterion "Consumer acceptance" ranged from 0.30 for the use of ozone to 1.00 for the use of no water disinfectant. The criterion "Economics" ranged from 0.33 for chlorine dioxide, ozone, and peracetic acid to 0.83 for free chlorine. The criterion "Health" had the broadest range of values, with scores from 0.25 for the use of free chlorine to 1.00 for the use of no water disinfectant (Table 3).

In food safety decision-making, the level of consumer protection should be maximized, while the costs and other adverse effects associated with a proposed control strategy should be minimized (Dunn, 2015). The scores in an MCDA provide the foundation for the analysis. Therefore, in our case study, the scores for the control strategies were based on peer-reviewed scientific research. For example, with the use of free chlorine, the costs are generally seen as less expensive than alternative water disinfection technologies (Banach et al., 2015; Garrido, Marin, Tudela, Allende, & Gil, 2019; Luo et al., 2011; Meireles et al., 2016). However, the potential health and environmental concerns from DBP formation, e.g., from trihalomethanes (THMs), makes it more controversial in terms of public health compared to other water disinfection technologies (Banach et al., 2015; Garrido et al., 2019; Meireles et al., 2016; Tudela, Lopez-Galvez, Allende, & Gil, 2019; Tudela, Lopez-Galvez, Allende, Hernandez, et al., 2019); these aspects were considered for the sub-criterion Possible side-effects. Also, free chlorine is reactive with organic matter (Garrido et al., 2019; Luo et al., 2011), more so than chlorine dioxide or peracetic acid (Banach et al., 2015), is sensitive to pH (Banach et al., 2015; Gil & Allende, 2018) and can be corrosive (Meireles et al., 2016); these aspects were considered when considering the sub-criterion Robustness.

By basing the scores on multiple factors, and in this case study, presetting the Effectiveness values, we aimed to control some bias coming from the stakeholder perspective. Moreover, we enhanced the experimental design of the MCDA by bringing varying degrees of complexity to the identified problem, such as including a time dimension (Mazzocchi et al., 2013). In our study, time (e.g., costs over five years) was included, which further allows the advantages and disadvantages of the technology to be assessed.

3.2. Response rate survey

The response rate of the 36 stakeholders surveyed was 50% (i.e., 18 replied). For each stakeholder group, the response rate was as follows: n = 2 (of 5) for fresh-cut processors, n = 3 (of 10) for producers and suppliers of disinfectants and equipment, n = 10 (of 12) for scientists, and n = 3 (of 9) for government representatives. All surveys were fully completed, although all three government representatives used the same points for more than two of the criteria. By doing so, this disproportionately influences the results coming from this stakeholder group. The effect of this response can be seen in the broader range of preferences for the government representatives and the very high values for the criterion "Health" (Table 4).

A limitation of this MCDA is the percentage of stakeholder respondents from producers and suppliers of disinfectants and equipment (30%) and government representatives (33%). Nonetheless, an advantage to this MCDA is the generally high response rate (50%) for an online survey, also considering that additional incentives, such as monetary response incentives, were not provided. In a study on survey response rates, Pedersen and Nielsen (2016) showed that surveys that appealed to an individual's egotistical need for approval resulted in an increased survey response rate. In this study, the survey e-mail used an altruistic text appeal (the results would be used in a scientific publication). Also, a somewhat egotistic text appeal was used - where the survey was personally addressed directly to each recipient, meaning they had been specially selected to participate. Another advantage of this MCDA is the high response rate (83%) for the stakeholder group scientists. Food safety requires that various technical information be considered from a multitude of scientific disciplines (Bartolini & Viaggi, 2010). Given the inclusive nature of the stakeholder group "scientists" in this study, several types of scientists could fit this profile and complement the needs for multiple scientific perspectives. Moreover, one could consider this stakeholder group to have the least amount of bias since there could be no economic or specific regulatory drive to come to a particular control strategy.

Results of the averaged preference weights for each criterion per stakeholder group are presented in Table 4. For the Technological aspects and Consumer acceptance criteria, the stakeholder group producers and suppliers of disinfectants and equipment rated it higher than the other groups. The weights for Economics were, in general, lower for all the other criteria, ranging from 8.8 to 14.2%. Given the low preference weight for Economics, further research to discern these values (e.g., quantitatively) is of lesser value than trying to estimate the determinants of Health. This criterion scored highest for all four stakeholder groups, with weights ranging from 25.3 to 46.1% (Table 4). The preference weights per stakeholder are shown in Appendix B, Table B.1.

Table 2
Scores of the control strategy per criteria after standardization of the original scenario with 1: best and 0: worst.

Control strategies	Criteria									
	Effectiveness	Technological aspects			Consumer acceptance		Economics		Health	
	Effectiveness	Ease of use	Robustness	Scale of the technology	Consumer perception	Organoleptic effects	Costs for producer	Reduction in water use	Possible side-effects	Workers' safety
1. Use free chlorine	1.00	0.70	0.67	1.00	0.30	0.67	0.67	1.00	0.00	0.50
2. Use chlorine dioxide	1.00	0.50	0.67	1.00	0.60	0.33	0.00	0.67	0.25	0.25
3. Use ozone	1.00	0.50	1.00	0.33	0.60	0.00	0.00	0.67	0.63	0.00
4. Use peracetic acid	1.00	0.70	0.67	0.67	0.60	0.33	0.33	0.33	0.63	0.75
5. Use no water disinfectant	0.00	1.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00

Table 3
Standardized performance scores, after averaging the scores of the sub-criteria, of the five main criteria per control strategy for the original scenario.

Control strategies	Criteria				
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health
1. Use free chlorine	1.00	0.79	0.48	0.83	0.25
2. Use chlorine dioxide	1.00	0.72	0.47	0.33	0.25
3. Use ozone	1.00	0.61	0.30	0.33	0.31
4. Use peracetic acid	1.00	0.68	0.47	0.33	0.69
5. Use no water disinfectant	0.00	0.33	1.00	0.50	1.00

Table 4
Preference weights of the criteria per stakeholder group for the original and alternative scenarios.

Stakeholders	Criteria					
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health	Sum (all)
Fresh-cut processors	20.0	18.0	21.6	11.6	28.8	100
Producers and suppliers of disinfectants and equipment	20.0	20.3	24.3	10.1	25.3	100
Scientists	20.0	18.2	22.3	14.2	25.4	100
Government	20.0	7.5	17.6	8.8	46.1	100

Using stakeholder weights in the analysis can increase uncertainty due to the subjectivity of the stakeholders and their own choices (Dunn, 2015). On the other hand, the preference weights can help to account for uncertainty in the case study and the case-specific nature of the risk (Van der Fels-Klerx et al., 2018). Therefore, the use of weighted preferences is two-sided, contributing subjectively to the MCDA as well as specifically to the case study. Ultimately, having the stakeholder input may increase the acceptance of the control strategy chosen.

This case study explored the use of an MCDA and was situated in the EU, with most respondents coming from the Netherlands. Herein, how culture impacts the criteria and "best" control strategies may be a relevant factor. Future case studies, following a similar approach, may consider comparing results per EU country or even more globally to elucidate the possible differences in the selected control strategy.

3.3. Ranking of control strategies

The global performance scores for each control strategy by criteria are reported per stakeholder group in Tables 5–8. Results for fresh-cut processors are shown in Table 5. The highest-ranked control strategy was peracetic acid, followed by using no water disinfectant and then free chlorine. Results for producers and suppliers of disinfectants and equipment, as well as scientists, are shown, respectively, in Tables 6 and 7. Similar to the fresh-cut processors, these two stakeholder groups had peracetic acid as the highest-ranked control strategy. However, the next best option differed; it was the use of free chlorine, followed by no water disinfectant. All three of these stakeholder groups had ranked ozone as the lowest control strategy. The results for government representatives are presented in Table 8. This stakeholder group ranked the use of no water disinfectant as the best control strategy, which differs from all other stakeholder groups. Also, the summed scores for each control strategy were the most varied in this group (range: 47.2–70.6, difference: 23.4) compared to all the other groups, where the difference in final scores for the control strategies ranged from 14.5 to 15.6. Also, the lowest control strategy for this stakeholder group was ozone (Table 8).

Each stakeholder respondent's global performance scores per control strategy were determined (Appendix C, Tables C.1 – C.18). Results showed that for fresh-cut processors (n = 2), the best control strategy was peracetic acid, and the worst was ozone (n = 2) (Tables C1 – C.2). This can be explained by the low scores for Economics. For producers and suppliers of disinfectants and equipment (n = 3), the best control strategy was either no water disinfectant (n = 2) or free chlorine (n = 1). At the same time, the worst was either ozone (n = 2) or the use of no water disinfectant (n = 1) (Tables C.3 – C.5). This can be explained by the high scores for Health and low scores for Economics, and in the case of free chlorine, the high scores for Technological aspects and low scores for Health. Results for scientists showed that the best control strategy was either peracetic acid (n = 6), free chlorine (n = 4), or no water disinfectant (n = 1). In contrast, the worst control strategy was either ozone (n = 10) or no water disinfectant (n = 1) (Tables C.6 – C.15). This can be explained by the high scores for Health and/or Technological aspects. For government representatives (n = 3), the best control strategy was either peracetic acid (n = 2) or the use of no water disinfectant (n = 1), while the worst was either ozone (n = 2) or chlorine dioxide (n = 1) (Table C.16 – C.18). This can be explained by the high scores for Health.

In this study, four stakeholder groups were chosen to participate in the analyses, and their input affects the outcome of the MCDA. The stakeholder group "fresh-cut processors" is financially and legally responsible for ensuring the quality and safety of their product. Ultimately, they need to choose the control strategy to apply during fresh-cut lettuce washing. Hence, it is most important that this group was considered in the analysis. The other three stakeholder groups' views are valuable since they provide insight into different judgments of value and help facilitate further discussion on the best control strategy. Other stakeholder groups, like non-governmental organizations (NGOs), retailers, or consumers, are interesting to consider in future case studies. These groups can represent the effects on the societal impact of the

Table 5
Global performance scores of control strategies for fresh-cut processors in the original scenario.

Control strategies	Criteria					
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health	Sum (all)
1. Use free chlorine	20.0	14.2	10.4	9.7	7.2	61.5
2. Use chlorine dioxide	20.0	13.0	10.1	3.9	7.2	54.1
3. Use ozone	20.0	11.0	6.5	3.9	9.0	50.3
4. Use peracetic acid	20.0	12.2	10.1	3.9	19.8	**65.9**
5. Use no water disinfectant	0.0	6.0	21.6	5.8	28.8	62.2

Table 6
Global performance scores of control strategies for producers and suppliers of disinfectants and equipment in the original scenario.

Control strategies	Criteria					
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health	Sum (all)
1. Use free chlorine	20.0	16.0	11.7	8.4	6.3	62.5
2. Use chlorine dioxide	20.0	14.6	11.3	3.4	6.3	55.7
3. Use ozone	20.0	12.4	7.3	3.4	7.9	51.0
4. Use peracetic acid	20.0	13.7	11.3	3.4	17.4	**65.9**
5. Use no water disinfectant	0.0	6.8	24.3	5.1	25.3	61.4

Table 7
Global performance scores of control strategies for scientists in the original scenario.

Control strategies	Criteria					
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health	Sum (all)
1. Use free chlorine	20.0	14.3	10.8	11.8	6.3	63.3
2. Use chlorine dioxide	20.0	13.1	10.4	4.7	6.3	54.6
3. Use ozone	20.0	11.1	6.7	4.7	7.9	50.4
4. Use peracetic acid	20.0	12.3	10.4	4.7	17.4	**64.9**
5. Use no water disinfectant	0.0	6.1	22.3	7.1	25.4	60.8

Table 8
Global performance scores of control strategies for government in the original scenario.

Control strategies	Criteria					
	Effectiveness	Technological aspects	Consumer acceptance	Economics	Health	Sum (all)
1. Use free chlorine	20.0	5.9	8.5	7.3	11.5	53.3
2. Use chlorine dioxide	20.0	5.4	8.2	2.9	11.5	48.1
3. Use ozone	20.0	4.6	5.3	2.9	14.4	47.2
4. Use peracetic acid	20.0	5.1	8.2	2.9	31.7	67.9
5. Use no water disinfectant	0.0	2.5	17.6	4.4	46.1	**70.6**

control strategy. The robustness of an MCDA is linked to the quality of the implemented scores and participation by stakeholder groups, including expert involvement in the exercise (Bartolini & Viaggi, 2010). Incorporating additional stakeholder groups into the analyses can affect the outcome and robustness of an MCDA. Stakeholder representation in an MCDA is important towards building a consensus in the ultimate decision, and its application in the food safety domain to assist in the decision-making process has been advocated (Fazil et al., 2008). Given the complexity in making food safety-related decisions, an MCDA approach has shown to be a suitable method that can be used to combine various outcomes with different scales (e.g., of quantitative, qualitative, and semi-quantitative data) during the decision-making process and can be used in future case studies.

A limitation to this MCDA is the input provided by the governmental representatives, which influenced the MCDA since participants provided the same points for two or more criteria despite the instructions presented, e.g., multiple zeros or low scores were used for some criteria. By providing scores in this way, this, in turn, inflated some (sub-) criteria, like those related to Health. On the other hand, since all participants from this group filled these criteria similarly, these results may accurately reflect the view of this stakeholder group. However, additional participation would help to affirm this result and decrease sample bias.

3.4. Final analysis and an alternative scenario

The effect of the weight of the criterion "Health" was of interest to evaluate given the results of the original scenario. In the alternative scenario, the effect that the weight of the criterion "Health," including the sub-criteria "Possible side-effects," was tested. The scores after the standardization of the alternative scenario are shown in Table 9. The results of our case study were compared to an alternative scenario

Table 9
Scores of the control strategy per criteria after standardization of the alternative scenario with 1: best and 0: worst.

Control strategies	Criteria									
	Effectiveness	Technological aspects			Consumer acceptance		Economics		Health	
	Effectiveness	Ease of use	Robustness	Scale of the technology	Consumer perception	Organoleptic effects	Costs for producer	Reduction in water use	Possible side-effects	Workers' safety
1. Use free chlorine	1.00	0.70	0.67	1.00	0.30	0.67	0.67	1.00	0.00	0.50
2. Use chlorine dioxide	1.00	0.50	0.67	1.00	0.60	0.33	0.00	0.67	**0.40**[a]	0.25
3. Use ozone	1.00	0.50	1.00	0.33	0.60	0.00	0.00	0.67	**0.70**[a]	0.00
4. Use peracetic acid	1.00	0.70	0.67	0.67	0.60	0.33	0.33	0.33	**0.70**[a]	0.75
5. Use no water disinfectant	0.00	1.00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00

[a] Represents where the score deviates from the original scenario after standardization; see Table 2 for comparison.

Table 10
Global performance scores of stakeholder groups and the final overall ranking per control strategy for the alternative scenario (Alt.), including the difference between the original scenario (Orig.) and alternative scenario (Δ).

Control strategies	Criteria										
	Fresh-cut processors		Producers and suppliers of disinfectants and equipment		Scientists		Government		Relative sum (all)[a]		
	Alt.	Δ	Alt.	Δ	Alt.	Δ	Alt.	Δ	Orig.	Alt.	Δ
1. Use free chlorine	61.5	0.0	62.5	0.0	63.3	0.0	53.3	0.0	3.6	3.6	0.0
2. Use chlorine dioxide	56.3	−2.2	57.6	−1.9	56.5	−1.9	51.5	−3.5	3.2	3.3	−0.1
3. Use ozone	51.4	−1.1	51.9	−1.0	51.4	−1.0	48.9	−1.7	3.0	3.0	0.0
4. Use peracetic acid	**67.0**	−1.1	**66.8**	−1.0	**65.8**	−1.0	69.7	−1.7	**4.0**	**4.0**	0.0
5. Use no water disinfectant	62.2	0.0	61.4	0.0	60.8	0.0	**70.6**	0.0	3.8	3.8	0.0

[a] Ratio of a score to the maximum score for the stakeholder group was aggregated across each stakeholder group to determine the "relative sum (all)."

(Table 10). The ratio of a score to the maximum score for the stakeholder group was aggregated across each stakeholder group to determine the "relative sum (all)" of a control strategy. These scores were then ranked amongst one another to come with the best overall control strategy. In both the original and alternative scenarios, overall, the best control strategy was the use of peracetic acid. This result has the same outcome for each stakeholder group, except for government representatives (Table 8, Table 10). Given the averaged results of the government representatives, the best option was the use of no water disinfectant, followed by peracetic acid. However, of the three-government representatives, two had found peracetic acid as the best control strategy (Table C.16; Table C.18), meaning the scores of the third government representative (Table C.17) shifted this overall best-choice for this stakeholder group. Furthermore, the next best control strategy overall was the use of no water disinfectant. This result is the same across all stakeholder groups except for producers and suppliers of disinfectants and equipment and scientists, whose next best control strategy was the use of free chlorine. Overall, the least likely control strategy for the case study was the use of ozone.

Using high concentrations of chlorine is linked to the increased presence of DBPs in the water and on the produce. One main concern with the use of free chlorine is the presence of THMs in the water; however, some research has shown that it does not correlate with higher DBPs on the produce (López-Gálvez, Tudela, Allende, & Gil, 2019). That study also showed, though, that different types of produce were shown to affect the characteristics of the wash water and that the use of a final rinse with tap water also reduced the concentration of DBPs on the produce (López-Gálvez et al., 2019). Another concern is the formation of other DBPs like 3-chlorotyrosine, which forms when hypochlorous acid reacts with tyrosine residues in proteins (Loan, Jacxsens, Kurshed, & De Meulenaer, 2016.) Research suggests that depending on the exposure from consuming foods like fresh-cut lettuce or spinach, 3-chlorotyrosine could be a health concern, and additional toxicological data is required to assess this risk (Loan et al., 2016; Komaki, Simpson, Choe, Plewa, & Mitch, 2018).

As outlined earlier, the score for the Possible side-effects of free chlorine was changed from 80 to 100 and analyzed in an alternative scenario. Given conflicting perspectives in the EU on the best disinfectant practices and effects of DBPs, comparing the change in this score provides an alternative take on the ultimate choice for control measures considering the worst-case or safest option (Table 10). Consequently, this change increased the standardized scores to be used for the criterion "Health" (Table 3) for the control strategies chlorine dioxide (0.25–0.33), ozone (0.31–0.35), and peracetic acid (0.69–0.73). Despite this change, the overall best control strategy remains peracetic acid, while the second-best option is the use of no water disinfectant (Table 10).

Any MCDA model has its limitations. The WSM chosen in this case study is a relatively simple model, and other MCDA models may also be applied to compare the final rankings. Recent research by Garre, Boué, Fernández, Membré, and Egea (2020) concluded that during an MCDA, the differences between models have a relevant impact on the outcome rankings. Uncertainty is a factor that highly influences the results, even more than the preference weights (Garre et al., 2020). In our case study, this could mean an alternative ranking to the best control strategy, peracetic acid. Within this WSM, there were no differences in the best final control strategy when the score changed from 80 to 100 for Possible side-effects of free chlorine. However, other changes to the original scores, due to uncertainty in the comparison of the control strategies, may lead to changes in the final outcome or ranking.

Although uncertainty is a factor that can limit an MCDA, the possibility of using several types of input on the scores in this study motivates the strength of this MCDA approach. The ease of use of a WSM makes it advantageous. Also, the outcome for the various stakeholders is understandable, and the differences in changing the scores or weights are transparent (Dunn, 2015). This advantage is evident in our case study, given the comparison of the final outcomes for two scenarios (Table 10), where the best-choice is peracetic acid for all stakeholder groups except government representatives.

4. Conclusion

Our study demonstrated the use of an MCDA method as a decision-making tool for a case study on choosing between alternative (mainly chemical) control strategies to treat the wash water that comes in direct contact with the produce in the wash tank during fresh-cut lettuce processing. The case study results showed that from the five control strategies, peracetic acid was found to be the overall best strategy to control pathogenic cross-contamination. Using an MCDA brought structure to the analysis while assisting in the decision-making process. The MCDA approach used in this case study can be used as a first step while evaluating control strategies on food safety themes like the cross-contamination of pathogens during food processing. We expect that using an MCDA approach will help increase the optimal allocation of resources towards the control strategy, as well as create balance and support for the decision to be selected.

Author contributions

J.L. Banach set-up the case study, provided input on the criteria and definitions, carried out the stakeholder survey and analyses, and wrote the main part of the manuscript. H.J. van der Fels-Klerx helped set up the case study and stakeholder survey. All authors critically interpreted the results, commented upon earlier versions of the manuscript, as well as read and approved the final manuscript.

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

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