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Life cycle assessment of active spring frost protection methods in viticulture in the Loire Valley and Champagne French regions

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ABSTRACT

Spring frosts have been identified as a significant threat to the wine sector, particularly in regions with early vine budbreak. The severity of frost damage varies depending on local climatic conditions, topography and other contextual factors. To protect vines, growers employ a range of techniques designed to increase the temperature around the buds. As climate change increases frost risk, several Active Spring Frost Protection Methods (ASFPMs) have emerged, often associated with high resource consumption and considerable labour demands. To support decision-making, Life Cycle Assessments (LCA) have been conducted on a comprehensive range of ASFPMs applied in the Loire Valley and Champagne French regions. These two regions differ in terms of ASFPM use, field management and local climatic conditions. Environmental assessments were performed using a context-specific LCA framework, taking into account context-specific factors such as application and climate variables. In total, six technologies of ASFPMs were compared: antifrost candles, wind machines, heaters, heating cables, sprinklers and winter cover. The Impact world + characterisation methodology was employed to calculate the following environmental indicators: Climate change, Fossil and nuclear energy use, Mineral resources use, Water scarcity, Terrestrial acidification, Human toxicity and Land occupation. Overall, wind machines and sprinklers showed better environmental performances than other technologies in both regions. However, sprinklers had the largest impact on the water scarcity indicator. Antifrost candles and fuel-fired heaters had the largest environmental impacts in the Loire Valley and Champagne regions, respectively. A sensitivity analysis based on the number of frost hours occurring during spring showed that instant ASFPMs, such as heaters and antifrost candles, exhibited greater variability due to their high direct emissions during use. In contrast, ASFPMs requiring fixed infrastructure, such as wind machines, sprinklers, winter covers and heating cables, showed less variability due to their lower fuel consumption per hectare. The integration of context-specific factors proved essential in this comparison, as the environmental ranking of ASFPMs was influenced by the number of frost hours in each region. For future research endeavours, it would be relevant to include ASFPM in the overall environmental assessment of the viticulture stage to determine its contribution and increase the robustness of the environmental performance of the viticulture stage.

KEYWORDS: environmental assessment, antifrost practices, wine-growing, vineyard, LCA

INTRODUCTION

Grape yields are affected by weather events and conditions at specific phenological stages during the growing season, such as budbreak and flowering (Belliveau *et al.,* 2006). Among weather events, spring frost can significantly reduce grape yield in several wine-growing regions (De Rosa *et al.,* 2021; Dinu *et al.,* 2021; Schultze *et al.,* 2016). Global warming disrupts the phenological cycle of grapevines, with a one-degree rise in average temperature projected to advance budbreak by seven to ten days (Bernáth *et al.,* 2021; Droulia & Charalampopoulos, 2021; Fraga *et al.,* 2012; Santos *et al.,* 2020; van Leeuwen *et al.,* 2019; Webb *et al.,* 2012). Consequently, this shift increases the vulnerability of wine crops to freezing temperatures during this critical stage (Kartschall *et al.,* 2015). Climate models coupled with phenological studies suggest that the frequency of spring frost events will increase in regions like Alsace, Burgundy and Champagne in France (Sgubin *et al.,* 2018), as well as in the UK and Germany (Kartschall *et al.,* 2015; Mosedale *et al.,* 2015). Additionally, spring frost is harmful in the Loire Valley French region as the sensitive grape varieties such as Chenin or Cabernet Franc are located in frost-prone areas (Neethling *et al.,* 2017).

Spring frosts occur when temperatures drop below freezing during bud break and two types of frost can take place: radiative frost and advective frost. Radiative frost is a nocturnal phenomenon that occurs under calm atmospheric conditions with weak or no winds and clear skies. At night, the soil releases accumulated solar heat from the day as infrared radiation, which is dispersed into higher-altitude air layers, potentially leading to a thermal inversion (Poling, 2008). As a result, the colder air near the soil becomes trapped, flowing downhill due to gravity. This effect is exacerbated in low-lying areas with bowl-shaped topography or obstructed airflow, where katabatic winds and downhill cold airflows, become stationary and intensify frost risks (Snyder & De Melo-Abreu,2005). Radiative frost is common in French wine regions during spring (Rochard *et al.,* 2019). In contrast, advective frost can occur both day and night and involves the movement of cold air masses, below 0 °C, driven by moderate to strong winds (Poling, 2008). This type of frost is particularly severe at high-altitude plateaus but remains rare in spring in France, typically associated with winter conditions (Rochard *et al.,* 2019).

To mitigate the impacts of spring frost on wine crops, several field practices are applied, categorised into Active Spring Frost Protection Methods (ASFPM) and Passive Spring Frost Protection Methods (PSFPM), also known as indirect methods (Poni *et al.,* 2022; Rochard *et al.,* 2019). PSFPM encompass all agronomic and preventive practices, such as soil management and late pruning, that enhance the plant's frost resistance, delay the bud development and indirectly improve the local climate, such as rising temperatures (Liu & Sherif, 2019; Poni *et al.,* 2022; Rochard *et al.,* 2019). Nonetheless, these methods are not always sufficient, so they are often combined with ASFPMs in highly frost-prone situations. ASFPMs directly modify the local microclimate by raising the temperature in a specific area to minimise the risk of frost damage. Different types of ASFPMs are distinguished in the literature, such as air mixing, direct heating, warm air dynamic transfer (Rochard *et al.,* 2019), reduction of long-wave radiation loss and overhead irrigation (De Melo-Abreu *et al.,* 2016).

ASFPMs are often criticised for being labour-intensive, expensive and particularly environmentally unfriendly, as they require significant amounts of energy and resources (Liu & Sherif, 2019). To assess the environmental impacts of systems, Life Cycle Assessment (LCA) has been considered as the multicriteria methodology of reference since 2006 (Jolliet *et al.,* 2010). LCA is based on the life cycle thinking covering different steps of the product or service life cycle and it evaluates several environmental indicators, such as Climate change (kg CO_2 equivalent), Eutrophication (kg of P), or Water scarcity (m^3). To identify best environmental practices in agriculture, LCA has proven its robustness in terms of methodology over more than a decade of use, especially in viticulture (Ferrara & De Feo, 2018; Renaud-Gentié, 2015; Rouault *et al.,* 2016). The viticulture stage is one of the most impactful stages in the LCAs of wine production, presenting high variability in environmental scores due to its diverse management practices (Ferrara & De Feo, 2018) and pedoclimatic conditions, especially regarding the use of phytosanitary products (Peña *et al.,* 2018; Renaud-Gentié *et al.,* 2014; Santos *et al.,* 2020). One of the main impacts of the viticulture stage relates to climate change and freshwater ecotoxicity indicators, largely driven by emissions from fuel consumption during mechanical practices (Renaud-Gentié *et al.,* 2019) and the production and transport of trellis posts and wires (Renaud-Gentié, 2015). Additionally, direct emissions from fertiliser and phytosanitary applications, as well as those from their productions, are major contributors to these two impact categories (Aranda *et al.,* 2005; Ardente *et al.,* 2006; Ferrara & De Feo, 2018; Gazulla *et al.,* 2010; Pizzigallo *et al.,* 2008). Among all LCA studies on wine production, none have yet included ASFPMs in the environmental assessment of the viticulture stage. Few studies assessed some environmental impacts of some ASFPMs dedicated to viticulture. Frota de Albuquerque Landi *et al*. (2021) assessed the environmental impacts of the innovative technology of ASFPM and compared it with an on-field classic wood burning; Pauthier *et al*. (2022) proposed a carbon footprint analysis coupled with efficiency and cost assessments to compare qualitatively seven ASFPMs. However, no comprehensive comparison of ASFPMs was done by LCA. Comparing the LCA impacts of diverse ASFPM systems, each reacting to different drivers for their activation, is complex. To address this, a methodology for context-specific LCA of ASFPMs has been proposed, which was illustrated using four contrasted ASFPMs. This methodology should now be applied to assess the environmental consequences of a broader range of ASFPM technologies in different contexts. This is essential for improving decision-making support for winegrowers and advisers. Additionally, comparing these technologies across

different contexts can highlight how context influences the environmental performance of ASFPMs. Such insights could guide regional stakeholders toward the most sustainable practices, facilitating better-informed funding decisions and encouraging ASFPM providers to reduce the environmental impacts of their solutions.

This study aims to identify differences in the environmental performances among various ASFPM technologies and analyse the potential influence of context-specific drivers. Compared to previous studies, it expands the scope to include the most widely used ASFPMs in France and identifies how different regional contexts affect the environmental comparison of these technologies. Additionally, the LCA of ASFPMs enables the identification of the main drivers of environmental impacts, which could contribute to eco-design opportunities for both ASFPM manufacturers and users.

A context-specific LCA was conducted to compare and evaluate six different ASFPM technologies, covering the most used practices in France and taking into account the impact of the context-specific drivers. To capture the effect of regional context, the application of the ASFPM technologies was studied in two distinct French wine regions: Loire Valley and Champagne, where the technologies are not applied to the same extent.

MATERIALS AND METHODS

1. LCA methodology applied to ASFPMs

The attributional LCA methodology is applied to assess the environmental performance of ASFPMs and consists of four iterative steps:

- Goal and scope definition: This step involves defining the goal of the study, the Functional Unit (FU), the assumptions and the system boundaries.
- Life Cycle Inventory (LCI): Data are collected and inputs/outputs calculations are performed for each Unit Process (UPR) within the defined study boundaries.
- Impact assessment: All relevant environmental indicators are calculated.
- Interpretation: The results are analysed and compared using internal findings and existing scientific and technical literature (Jolliet *et al.,* 2010).

The LCA modelling of ASFPMs is divided into sub-systems, including:

- Application: Covering direct emissions from water and energy use, along with their production processes, including extraction, treatment, as well as refining and combustion for fuels related to the use of equipment.
- Equipment manufacturing: Including the production and disposal of all equipment used for ASFPMs, as well as the paraffin for the antifrost candles.
- Transport: Accounting for the transport of materials.
- Implementation and Removal: Encompassing all practices and resources necessary for installing and removing the ASFPM from the field, including the transport of human labour from the farm to the vine plot.
- Fold and Unfold: Specific to the winter cover system, this involves folding and unfolding the cover when wind speed exceeds a specific threshold. It only includes the transport of human labour from the farm to the vine plot.

The system boundaries extend from resource extraction for the ASFPM to its end of life. The FU is initially defined as "using the ASFPM for one hour to protect one hectare of vine crop". The LCA is adjusted to include context-specific factors, such as winegrowers' application strategies and climatic conditions during the spring. After these adjustments, the FU becomes the following "to protect 1 ha of vine crop during one hour of frost". One hour of frost is defined as an hour when the average temperature drops below 0 degrees during the spring period, as specified by Poling (2008). Frost severity is not taken into account in the modelling; therefore, average fuel consumption values are used, including peat, wood, paraffin, fuel oil, gas and diesel. For the winter cover system, the FU is defined as "protecting one hectare of vine crop with one-fold and unfold operation. This approach follows the framework established by Baillet *et al.* (2024a) and Baillet *et al.* (2024b), which details the integration of these context-specific factors and the corresponding FU adjustments.

2. Data collection

Concerning Loire Valley cases, a previous study conducted by the Observatoire InterLoire identified the most commonly used ASFPMs in the Loire Valley region (TechniLoire, 2023). Then, fifteen interviews were carried out to perform the LCA of the most utilised ASFPMs. The interviews included twelve wine growers from the Loire Valley and a wine grower advisor. Concerning Champagne, a winegrower advisor and two environmental experts from the Champagne protected designation of origin institute CIVC were interviewed. The environmental expert from the Champagne region provided detailed ASFPM life cycle inventories specific to their territory, which were sourced from winegrowers he monitored during a past study. Transversally across both regions, a manufacturer of winter covers was interviewed to build the ASFPM life cycle inventory.

The objectives of these interviews were twofold:

1. To identify the technical characteristics of specific ASFPMs, including equipment details and technical information regarding installation and removal processes.
2. To understand the strategies employed by winegrowers during frost events in spring.

The technical characteristics gathered from these interviews, along with supplementary data from manufacturers and the data provided by the Champagne committee, were utilised to model the LCIs of ASFPMs. Data spanning from 2013 to 2023 were collected from two weather stations, Montreuil-Bellay and Epernay, encompassing hourly variables such as temperature, relative humidity and maximum windspeed.

Temperature and wind speed data are measured at 2 m above ground in both climatic stations. The Montreuil-Bellay station is located at an altitude of 60 m in the Maine-et-Loire territory of the Loire Valley region. The Epernay station is located at an altitude of 77 m in the Marne territory of the Champagne region.

The software SimaPro was used to model the LCA and perform a Monte Carlo uncertainty analysis (Firestone *et al.,* 1997), using Abribalyse 3.1.1 (Koch & Salou, 2022) and Ecoinvent 3.10 databases (Wernet *et al.,* 2016). Seven environmental impacts were calculated with the Impact World + v1.29 characterisation method, which integrates multiple state-of-the-art developments, including spatial and temporal differentiation of some environmental indicators (Bulle *et al.,* 2019):

- Climate Change Short Term (CC): Expressed in kg of CO_2 eq, this impact reflects the contribution of greenhouse gases to the rapid temperature increases.
- Fossil and Nuclear Energy (FU): Expressed in MJ deprived, this impact is determined by the resource's scarcity at a global scale.
- Mineral resources use (MR): Expressed in kg of deprived, this impact aims to assess the loss of functional value of the mineral resource
- Human Toxicity Cancer (HTC): Expressed in CTUh, this long-term indicator assesses human health risks.
- Terrestrial Acidification (A): Expressed in kg PO_4, this impact indicates changes in soil chemical properties.
- Land Occupation Biodiversity (LU): Expressed in m^2 yr arable, this impact accounts for both direct and indirect land use.
- Water Scarcity (W): Expressed in m^3 world eq, this impact evaluates regional water consumption against global water availability.

These indicators were selected based on the potential impacts of ASFPMs due to their high consumption of fossil and mineral resources, water and energy. Moreover, several ASFPMs require combustion processes to be effective and consequently have potential impacts on soil and human health. Additionally, an indicator that indirectly relates to biodiversity aspects is relevant to explore when evaluating agricultural systems such as vineyards. A Monte Carlo analysis was performed with 1000 iterations based on the uncertainty values from the databases and characterisation factors from the Impact World + methodology. Additionally, to enhance the LCA comparison of ASFPMs, the Environmental Footprint (EF) v3.1 characterisation method was applied to calculate corresponding indicators, including Climate Change, Resource Use (fossil), Resource Use (mineral and metal), Acidification, Human Toxicity Cancer, Land Use and Water Use (Andreasi Bassi *et al.,* 2023). Supplementary data provide detailed charts, ensuring consistency with the graphical results section for comparison and further insights.

3. ASFPM descriptions

The following ASFPM technologies were compared and analysed in both the Loire Valley and Champagne regions:

- Winter cover: This protective layer shields one or two rows of vines and is secured to adjacent layers with elastics. Together, these layers cover the entire plot to retain daytime warmth during spring frost. The plastic layer reflects the radiative waves from the soil back to the vines. When windspeeds are forecasted to exceed 12 m/s, the winter protection is folded around the vine trellis wire to prevent damage to the elastic, cover and trellis system. Such windspeed combined with temperature below 0 °C can occur during advective frost. Consequently, this system is primarily designed to protect against radiative frost and is a semi-permanent infrastructure.
- Wind machines: these devices mix hot air with the colder layer during spring frost events. They facilitate the mixing of positive temperatures at altitude with sub-zero temperatures near the ground, reducing the risk of frost damage. Wind machines don't always bring temperatures up, but rather slow down the natural cooling of the layers close to the surface (Le Cap, 2023). Different power sources can drive these devices including thermic engines, electric motors and gas engines. Additionally, they can be tractor-powered, directly connected to the tractor's power take-off. They are often combined with scattered anti-frost candles or small heaters filled with combustibles in the protected area. Additionally, wind machines can be paired with a burner placed in front, which theoretically warms the air layer before it mixes with the lower air layer through the wind machine's propellers. However, the heat gained with the additional burner has not been uniformly successful over the past trials (Evans, 2000). While activation is typically monitored manually, automatic capabilities are available. Wind machines can be either mobile, serving as semi-permanent infrastructure, or fixed, representing a permanent solution.
- Sprinklers: Originally designed for irrigation, sprinklers are utilised to cover vine buds with water before temperatures drop below freezing, maintaining the bud temperature at 0 °C or above. When the water freezes, the phase change releases heat and forms an insulating ice layer. As a result, vine buds absorb this released heat. While automated activation is possible, it can be risky without the right conditions, as it requires a constant water supply during specific climatic conditions. This method necessitates a permanent underground piping system and a semi-permanent overground irrigation system.
- Antifrost candles: These candles are lit last minute to warm the air around vine buds. Several candles are necessary to effectively protect a full plot, with approximately 350 candles for 1 hectare of vine crop in the Loire Valley and around 500 in the Champagne region, depending on frost severity. This method requires constant monitoring during application and represents an instant solution, as no prior setup is necessary before spring frost events.
- Heating cables: Electric cables are attached to the vine wires to heat the surrounding area within a radius of 5 to

TABLE 1. Scenarios of application to use efficiently SFPM for the first level of contextualisation.

Type of ASFPM	Activation climatic conditions	Deactivation climatic conditions
Wind machine	Dry temperature under 0.5 °C	Dry temperature above 2.5 °C
Heater	Dry temperature under 0.5 °C	Dry temperature above 2 °C
Antifrost candle	Dry temperature under 0.5 °C	Dry temperature above 2 °C
Sprinkler	Wet temperature under 2.5 °C	Wet temperature above 2.5 °C
Heating cable	Dry temperature under 0.5 °C	Dry temperature above 0.5 °C
Winter cover	Maximal wind speed under 12.5 m/s	Maximal wind speed above 12.5 m/s

TABLE 2. Total of spring frost hours per year from the climatic stations "Epernay" and "Montreuil-Bellay".

Spring season (start of April–end of May)	Number of frost hours from Epernay station at 2 m above the soil (Champagne region)	Number of frost hours from Montreuil-Bellay station at 2 m above the soil (Loire Valley region)
2013	5	2
2014	0	0
2015	2	0
2016	0	1
2017	3	0
2018	0	0
2019	8	3
2020	3	0
2021	24	11
2022	10	10
2023	2	2
Total	61	29

10 cm through electrical conductivity. These cables must be connected to a control unit powered by a generator or the national electric network. This solution can be semi-permanent, involving complete installation and removal of all equipment before and after the spring frost period, or, partially permanent, wherein an underground system is installed and connected to the national electric grid.

– Heaters: these are metal containers that burn fuel, wood, or peat to warm the air around the vine buds. Each heater has a lifespan of approximately 25 uses with around 180 heaters required to protect 1 hectare of vine crop in the Loire Valley and 200 in the Champagne region. Heaters necessitate installation before frost events and require monitoring during use.

Similar application scenarios for efficient ASFPM use were identified in both the Loire Valley and Champagne regions, as summarised in Table 1. Heaters and antifrost candles share common application strategies, along with heating cables. Climatic scenarios, based on cumulative frost hours per spring season from 2013 to 2023, are detailed in Table 2. In this study, 24 ASFPMs were assessed: 14 were applied in the Loire Valley and 11 in the Champagne region. Among the studied ASFPMs, the breakdown includes 1 winter cover, 2 sprinklers, 3 antifrost candles, 3 heating cables, 5 heaters and 11 wind machines. Among the wind machines, 4 are mobile and can be removed from the vine plots after spring and 7 are fixed, anchored with a cement base. Details of each assessed ASFPM are presented in Table 3. Notably, the fixed wind machines are taller than the mobile ones. The details of the ASFPMs models can be retrieved in the dataset from Baillet *et al.* (2024a) available in the French national open database. Each modelled ASFPM is unique, derived from the outcome of the interviews conducted on the field with either the farmers or the manufacturers.

4. Characteristics of Loire Valley and Champagne Regions

Loire Valley region, located in western France, is renowned for its diverse grape production, with 60 different wine appellations of origin. Most of the wine-growers interviewed were situated in the southern part of the region, between the cities of Angers and Saumur. This specific area has become increasingly vulnerable to frost events over the past decade due to global warming (Neethling *et al.,* 2017) and exhibits a wide range of ASFPMs. Under different climatic projections, the risk of frost damage on vine crops will increase due to the phenological disturbances and will affect other western French regions (Petitjean *et al.,* 2022). The main grape

TABLE 3. Labelling for all ASFPMs compared in both French regions.

Label	Type of ASFPM	Region	Highlighted detail
AC1-C	Antifrost candles	Champagne region	Petrol as a raw material
AC2-C	Antifrost candles	Champagne region	Palm oil as a raw material
AC1-V	Antifrost candles	Loire Valley region	Petrol as a raw material
FWM1-C	Wind machine	Champagne region	Fixed machine, gas fuel, with small heaters
FWM2-C	Wind machine	Champagne region	Fixed machine, gas fuel, without small heaters
FWM3-C	Wind machine	Champagne region	Fixed machine, gas fuel, with burner
MWM1-C	Wind machine	Champagne region	Mobile machine, diesel fuel, with a small heater
MWM2-C	Wind machine	Champagne region	Mobile machine, diesel fuel, with burner
FWM1-V	Wind machine	Loire Valley region	Fixed machine, diesel fuel, with small heaters
FWM2-V	Wind machine	Loire Valley region	Fixed, gas fuel, with small heaters
FWM3-V	Wind machine	Loire Valley region	Fixed, diesel fuel, without small heaters
FWM4-V	Wind machine	Loire Valley region	Fixed, diesel fuel, with burner
MWM1-V	Wind machine	Loire Valley region	Mobile, diesel fuel, with a small heater and generator
MWM2-V	Wind machine	Loire Valley region	Mobile, diesel fuel, with a small heater
H1-C	Heater	Champagne region	Use fuel as an energy resource
H2-C	Heater	Champagne region	Use wood as an energy resource
H1-V	Heater	Loire Valley region	Use fuel as an energy resource
H2-V	Heater	Loire Valley region	Use wood as an energy resource
H3-V	Heater	Loire Valley region	Use peat as an energy resource
HC1-C	Heating cable	Champagne region	Copper cable
HC1-V	Heating cable	Loire Valley region	Copper cable
HC2-V	Heating cable	Loire Valley region	Radiative cable with diode
S1-C	Sprinkler	Champagne region	50 m^3 of direct water consumption
S1-V	Sprinkler	Loire Valley region	35 m^3 of direct water consumption
WC1-V	Winter cover	Loire Valley region	Non-woven polypropylene cover

varieties in Loire Valley are Cabernet franc and Chenin, the latter being particularly sensitive to spring frost due to its early budburst.

Champagne, by contrast, is one of the most experienced regions in France when it comes to spring frost protection methods. The climate and topography of its vineyard make it especially prone to spring frost events. As a result, wine growers and advisers in this region are highly skilled in spring frost protection practices, enhancing the robustness of the study in terms of application scenarios and ASFPM analyses.

These two regions are particularly relevant for analysing the influence of different climatic conditions and plantation densities on the environmental performances of ASFPMs. Although similar ASFPMs may be used in both regions, variations in vineyard management practices provide valuable insights when comparing the environmental impacts under a context-specific LCA framework.

RESULTS

1. Comparison of global ASFPM's environmental performances

The environmental impacts of ASFPMs from the Loire Valley and Champagne regions are compared depending on frost hours in Figures 1 and 2, respectively. The theoretical variation of frost hours is based on the 2018 and 2021 millesimal, corresponding to the years in which the maximum and minimum frost hours occurred in spring (April and May) in both French regions over the 2013–2023 decade, respectively. A one-step variation is then performed between the minimum and maximum values. Each number of frost hours corresponds to a comparative LCA in both regions, where the global score of each indicator is presented.

In the Loire Valley region shown in Figure 1, HC2-V, which corresponds to the heating cable with lightning diode, shows the highest scores for all environmental indicators when the frost occurrence is zero, except for the land occupation category. This is mainly due to the high impact of its manufacture and disposal. However, if the frost occurrence is above zero, the hierarchy of environmental performance of the ASFPMs changes. H1-V, corresponding to fuel-fired heaters, has the highest score for the Climate change, Fossil and nuclear energy use and Terrestrial acidification indicators due to its high fuel consumption. AC1-V, corresponding to petrol-based antifrost candles, shows the highest score for the Mineral resources use and Human toxicity cancer indicators, due to the use of paraffin increasing with frost hours. For the Water scarcity and Land occupation indicators, S1-V and H2-V, corresponding to sprinklers and wood-burning heaters respectively, have the highest score. For S1-V, this is mainly due to the direct water consumption during its application, which corresponds to 35 m^3/h/ha. The high impact of H2-V on Land occupation is due to its high demand for wood for application. Wind machines, closely followed by sprinklers, perform better than the other technologies in all environmental categories, except for the Mineral resources use indicator where the sprinkler has the lowest impact. Wind machines have a lower impact due to their wide range of protection for a relatively low resource consumption, but still require a heavy steel-based infrastructure, which explains their higher impact on the Mineral resources use indicator than sprinklers. For all the environmental indicators, the hierarchy of the environmental scores of the ASFPMs stabilises after 5 hours of frost in the Loire Valley region.

In the Champagne region, AC2-C, corresponding to palm oil-based antifrost candle, has the highest score for all environmental indicators, regardless of frost occurrence, except for the Fossil and nuclear energy use category. This can be explained by the high consumption of palm oil-based paraffin, as palm oil has a low calorific potential and its production has a high environmental impact, especially when it is responsible for deforestation. H1-C, which corresponds to fuel-fired heaters, has the highest impact on the Fossil and nuclear energy use category, closely followed by the AC1-C petrol-based antifrost candle, when the frost occurrence is lower than 5. When frost occurrence increases, AC1-C has the highest impact on the Fossil and nuclear energy use indicator,

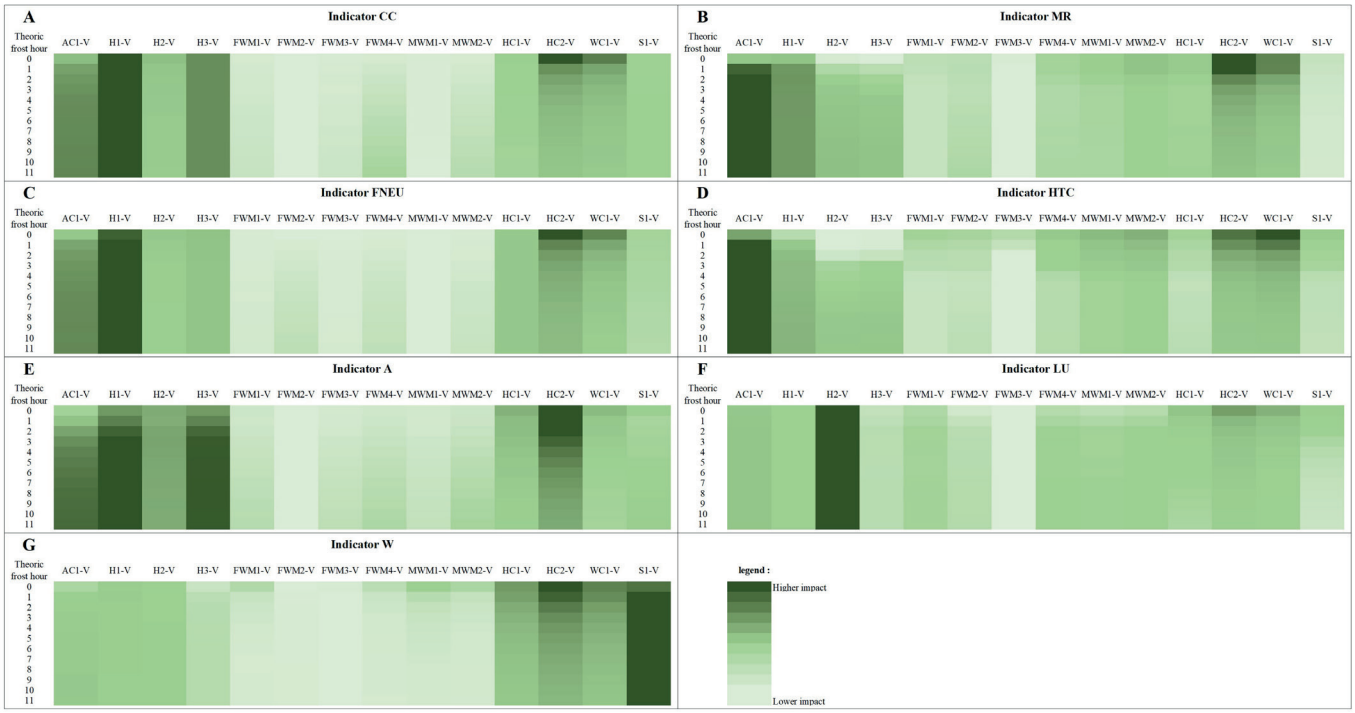


FIGURE 1. Comparison of ASFPMs' environmental impacts from Loire Valley region in function of yearly spring frost hour occurrences.

Seven heatmaps display the ASFPMs' environmental score of the Loire Valley region depending on the frost occurrence. Darker colours correspond to higher scores in the impact category. The frost occurrence varies from 0 to 11 corresponding to the 2018 and 2021 millesimal (Table 2), respectively. A: Climate Change, short term. B: Mineral resources use. C: Fossil and nuclear energy use. D: Human toxicity cancer. E: Terrestrial acidification. F: Land occupation, biodiversity. G: Water scarcity. AC1-V: antifrost candles, Loire Valley region, petrol as raw material. FWM1-V: wind machine, Loire Valley region, fixed machine, diesel fuel, with small heaters. FWM2-V: wind machine, Loire Valley region, fixed, gas fuel, with small heaters. FWM3-V: wind machine, Loire Valley region, fixed, diesel fuel, without small heaters. FWM4-V: wind machine, Loire Valley region, fixed, diesel fuel, with burner. MWM1-V: wind machine, Loire Valley region, mobile, diesel fuel, with small heater and generator. MWM2-V: wind machine, Loire Valley region, mobile, diesel fuel, with a small heater. H1-V: heater, Loire Valley region, fuel as an energy resource. H2-V: heater, Loire Valley region, uses wood as an energy resource. H3-V: heater, Loire Valley region, uses peat as an energy resource. HC1-V: heating cable, Loire Valley region, copper cable. HC2-V: heating cable, Loire Valley region, radiative cable with diode. S1-V: sprinkler, Loire Valley region, 35 m^3 of direct water consumption. WC1-V: winter cover, Loire Valley region, non-woven polypropylene cover.

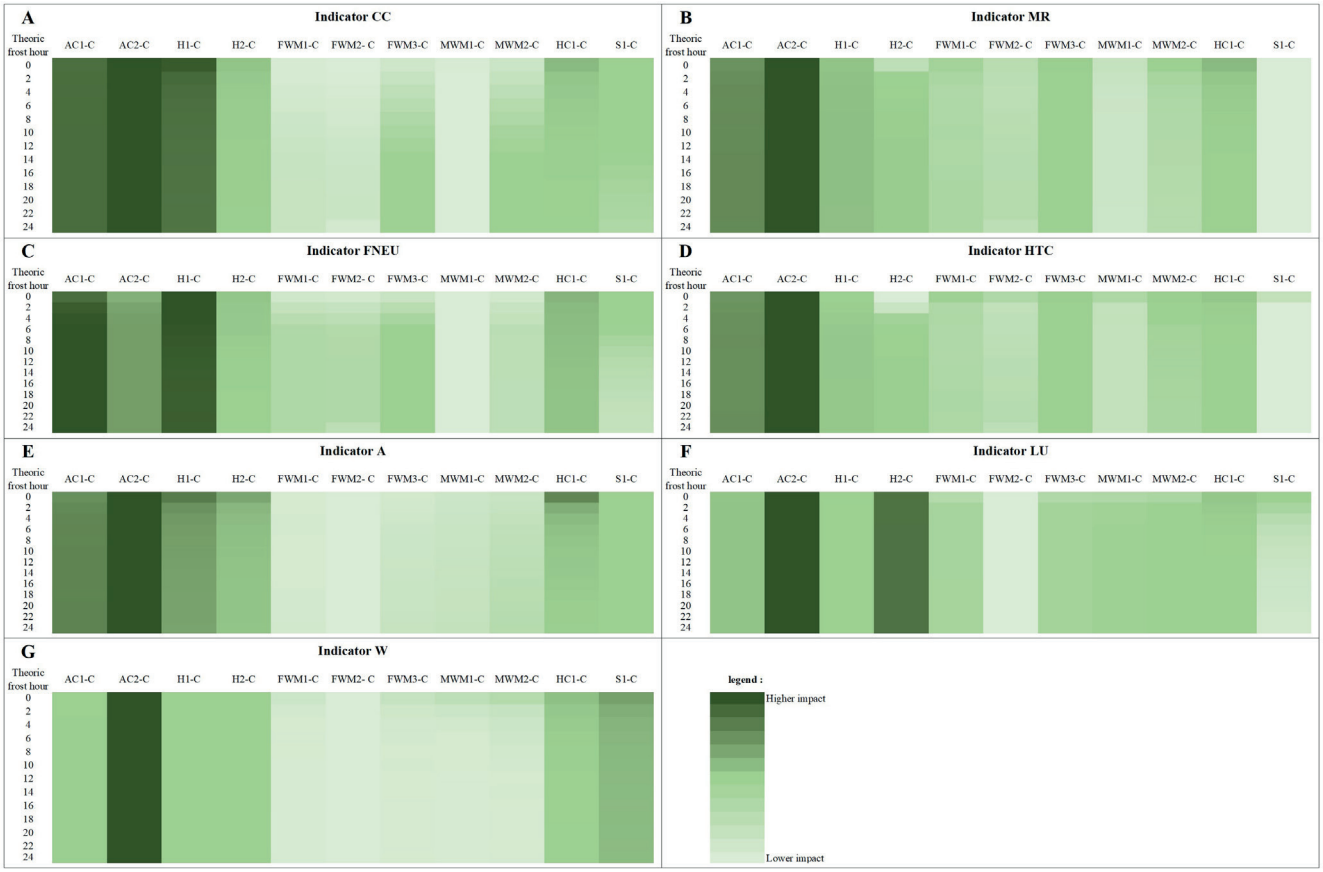


FIGURE 2. Comparison of ASFPMs' environmental impacts from the Champagne region in the function of yearly spring frost hour occurrences.

Seven heatmaps display the ASFPMs' environmental score of the Champagne region depending on the frost occurrence. Darker colours correspond to higher scores in the impact category. The frost occurrence varies from 0 to 24 corresponding to the 2018 and 2021 millesimal (Table 2), respectively. A: Climate Change, short term. B: Mineral resources use. C: Fossil and nuclear energy use. D: Human toxicity cancer. E: Terrestrial acidification. F: Land occupation, biodiversity. G: Water scarcity. AC1-C: antifrost candles, champagne region, petrol as raw material. AC2-C: antifrost candles, champagne region, palm oil as raw material. FWM1-C: wind machine, Champagne region, fixed machine, gas fuel, with small heaters. FWM2-C: wind machine, Champagne region, fixed machine, gas fuel, without small heaters. FWM3-C: wind machine, Champagne region, fixed machine, gas fuel, with burner. MWM1-C: wind machine, Champagne region, mobile machine, diesel fuel, with a small heater. MWM2-C: wind machine, Champagne region, mobile machine, diesel fuel, with burner. H1-C: heater, Champagne region, fuel as an energy resource. H2-C: heater, Champagne region, wood as an energy resource. HC1-C: heating cable, Champagne region, copper cable. HC1-V: heating cable, Loire Valley region, copper cable. S1-C: sprinkler, Champagne region, 50 m^3 of direct water consumption.

closely followed by H1-C. This high impact is mainly driven by the consumption of fuel and paraffin, respectively. The S1-C sprinkler has the lowest score for the Mineral resources use indicator, regardless of frost occurrence, because its main equipment is based on plastic pipes and aluminium poles. For the Human toxicity cancer indicator, the wood-burning heater has the lowest score when frost hours are less than 2. However, as frost hours increase, the S1-C sprinkler and the FWM1-C, FWM2-C and MWM1-C wind machines have lower scores than all other ASFPMs. The FWM3-C and MWM2-C wind machines have higher environmental scores than the other wind machine ASFPMs for all indicators, especially as frost occurrence increases. This is mainly due to the use of a burner in front of the wind machines, involving a higher demand for fuel resources.

2. Hotspots' analysis of ASFPM's environmental performances

Figure 3 illustrates the largest contributions and sources of variability in the environmental performance of ASFPMs for each indicator in the Loire Valley region. First, it details the main contributors for each environmental indicator, highlighting which ASFPM sub-systems have the most significant impact on specific environmental categories. Then, it explains how the variability in the environmental performance of ASFPM sub-systems is influenced by the variation in frost hours, demonstrating how changes in frost duration affect the overall environmental impact of these technologies.

The application sub-system corresponds to the impact of the direct use of ASFPMs. It presents the largest contribution in the Climate change indicator for AC1-V, H1-V, H3-V, FWM2-V, FWM4-V and MWM2-V regardless of frost

occurrence. It can be explained by the high demand for fuel resources during their direct application, such as petrol-based paraffin for AC1-V, fuel for H1-V, peat for H3-V, gas and wood for FWM2-V, diesel for the burner of FWM4-V and wood and diesel for MWM2-V. However, for H2-V, FWM1-V, FWM3-V and MWM1-V, the application sub-system is the largest contributor when the frost occurrence is high. For FWM1-V, FWM3-V and MWM1-V, their application sub-system impacts are lower than the other wind machines as they use less fuel resources. For H2-V, its direct application sub-system is initially less impacting than the other heaters as its type of fuel resource is wood. For the Climate change indicator, the equipment manufacturing sub-system is the largest contributor for S1-V, WC1-V, HC1-V and HC2-V regardless of frost occurrence. This can be explained by the high demand for resources in their equipment, such as different types of plastic for the pipes of S1-V, the cover of WC1-V and the cables of HC1-V and HC2-V. Moreover, this is also due to their overall low, or null for WC1-V, consumption of fuel resources during their application. However, for FWM1-V, FWM3-V and MWM1-V, the equipment manufacturing sub-system is the largest contributor to the Climate change indicator when frost hours are low.

For the Fossil and nuclear energy use indicator, the equipment manufacturing sub-system is the largest contributor for AC1-V, WC1-V and S1-V due to the consumption of paraffin and plastic-based resources, respectively. For the same indicator, the application sub-system is the largest contributor for FWM1-V, FWM2-V, FWM3-V, FWM4-V, MWM1-V, MWM2-V, H1-V and H3-V regardless of frost occurrence due to their high direct consumption of fuel resources. For H2-V and HC1-V, the application subsystem is the largest contributor when the frost occurrence is high, otherwise the equipment manufacturing subsystem is the largest contributor.

For the Mineral resources use indicator, the equipment manufacturing sub-system is the largest contributor for all ASFPMs, except for H1-V, where it is the application sub-system, regardless of frost occurrence. This is due to the high indirect impact of producing light fuel for the direct application of H1-V.

For the Human toxicity cancer indicator, the equipment manufacturing sub-system is the largest contributor for all ASFPMs, except for H1-V. Indeed, the production of metal-based and plastic-based structures is one of the main drivers of Human toxicity cancer indicators. For H1-V, the application sub-system is the most impactful due to the production of fossil fuel resources.

For the Terrestrial acidification indicator, the application sub-system is the most impactful for H1-V, H2-V, H3-V, FWM1-V, FWM3-V, FWM4-V, MWM1-V, MWM2-V and S1-V regardless of frost hour occurrence, mainly driven by the combustion of fuel resources. For AC1-V, HC1-V, HC2-V and WC1-V, the equipment manufacturing sub-system is the largest contributor, regardless of frost occurrence, as no combustion is required for the application of HC1-V, HC2-V and WC1-V and as the paraffin production of AC1-V has higher impacts than its combustion.

For the Land occupation indicator, the equipment manufacturing sub-system is the largest contributor for AC1-V due to the paraffin manufacturing, HC1-V and HC2-V due to the cable production, WC1-V mainly driven by the cotton production for the elastics and S1-V due to the production of aluminium poles. For the same indicator, the application sub-system is the largest contributor for H1-V, H2-V, H3-V, FWM1-V, FWM2-V, FWM4-V, MWM1-V and MWM2-V regardless of frost occurrence, because of the production of resource fuel.

For the Water scarcity indicator, the largest contributor is the equipment manufacturing sub-system for AC1-V due to the paraffin production, FWM1-V, FWM2-V, FWM3-V, FWM4-V, MWM1-V and MWM2-V due to the metal production for the infrastructure and engine, HC1-V and HC2-V due to the cable production and WC1-V due to the plastic production of the cover. For the same indicator, the application sub-system is the largest contributor regardless of frost occurrence for S1-V due to its direct water consumption and H1-V, H2-V and H3-V due to their fuel resources consumption.

For AC1-V, H1-V, H2-V and H3-V, the main source of variability in all environmental categories can be explained by the overall equipment manufacturing due to the consumption of mineral resources and the application sub-systems due to the consumption of fuel resources, both depending on frost occurrence. For AC1-V, H1-V and H3-V, the transport subsystem contributes to the variability of Climate change and Fossil and nuclear energy use indicators as more candles or heaters are required if the frost hours increase. For FWM1-V, FWM2-V, FWM3-V, FWM4-V, MWM1-V, MWM2-V, HC1-V, HC2-V and S1-V, the application sub-system is the main source of score variability for all indicators as more fuel is required to their applications, except for the Human toxicity cancer indicator because it is mainly influenced by the infrastructure manufacturing. The equipment implementation sub-system is the source of variability in the environmental score for WC1-V, except for the Human toxicity cancer and Terrestrial acidification indicators. The sub-systems “removal of equipment” and “implementation of equipment” are responsible for the score variability for AC1-V in all indicators, except for the Human toxicity cancer indicator.

Figure 4 presents the largest contributions and sources of variability of the ASFPMs for each environmental indicator in the Champagne region. The application sub-system is the largest contributor to the Climate change indicator for AC1-C, H1-C, H2-C, FWM1-C, FWM2-C, FWM3-C, MWM1-C and MWM2-C regardless of frost occurrence, due to the combustion of fuel resources. For the Climate change indicator, the equipment manufacturing sub-system is the largest contributor regardless of frost hours for S1-C due to

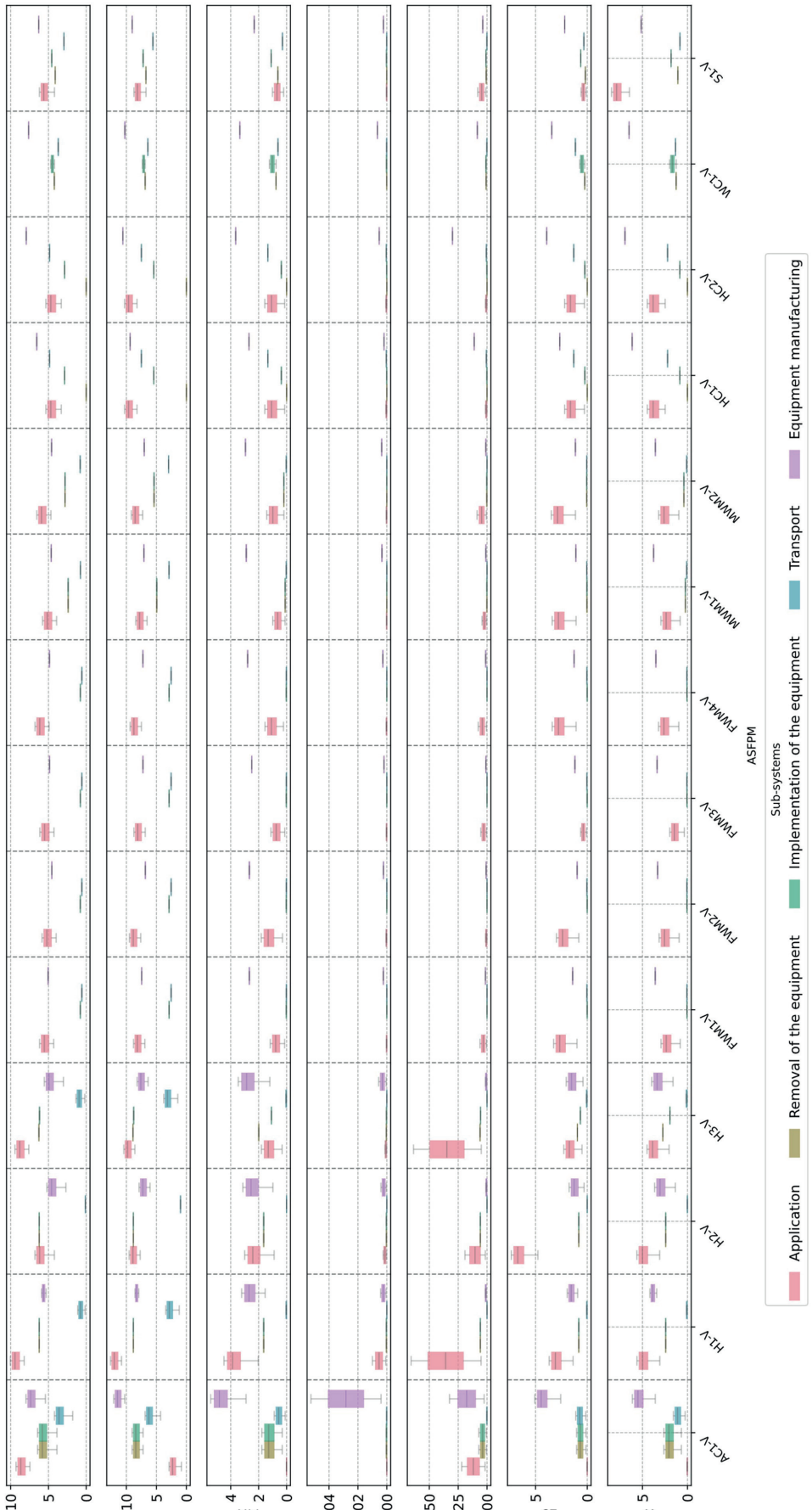


FIGURE 3. Comparison of the sub-system impact's variation for all ASFPMs of the Loire Valley region through the selected LCA indicators.

CC: Climate change short term in kg of CO_2 eq. FNEU: Fossil and nuclear energy use in MJ deprived. MR: Mineral resource use in kg deprived. HTC: Human toxicity cancer in CTUh. A: Terrestrial acidification in kg of SO_2 eq. LU: Land occupation biodiversity in m^2/yr arable. W: Water scarcity in m^3 world eq. The y-axis represents the indicator score in log (1 + specific indicator value) per type of ASFPM technology. AC1-V: antifrost candles, Loire Valley region, petrol as raw material. FWM1-V: wind machine, Loire Valley region, fixed machine, diesel fuel, with small heaters. FWM2-V: wind machine, Loire Valley region, fixed, gas fuel, with small heaters. FWM3-V: wind machine, Loire Valley region, fixed, diesel fuel, without small heaters. FWM4-V: wind machine, Loire Valley region, fixed, diesel fuel, with burner. MWM1-V: wind machine, Loire Valley region, mobile, diesel fuel, with small heater and generator. MWM2-V: wind machine, Loire Valley region, mobile, diesel fuel, with a small heater. H1-V: heater, Loire Valley region, fuel as an energy resource. H2-V: heater, Loire Valley region, uses wood as an energy resource. H3-V: heater, Loire Valley region, uses peat as an energy resource. HC1-V: heating cable, Loire Valley region, copper cable. HC2-V: heating cable, Loire Valley region, radiative cable with diode. S1-V: sprinkler, Loire Valley region, 35 m^3 of direct water consumption. WC1-V: winter cover, Loire Valley region, non-woven polypropylene cover.

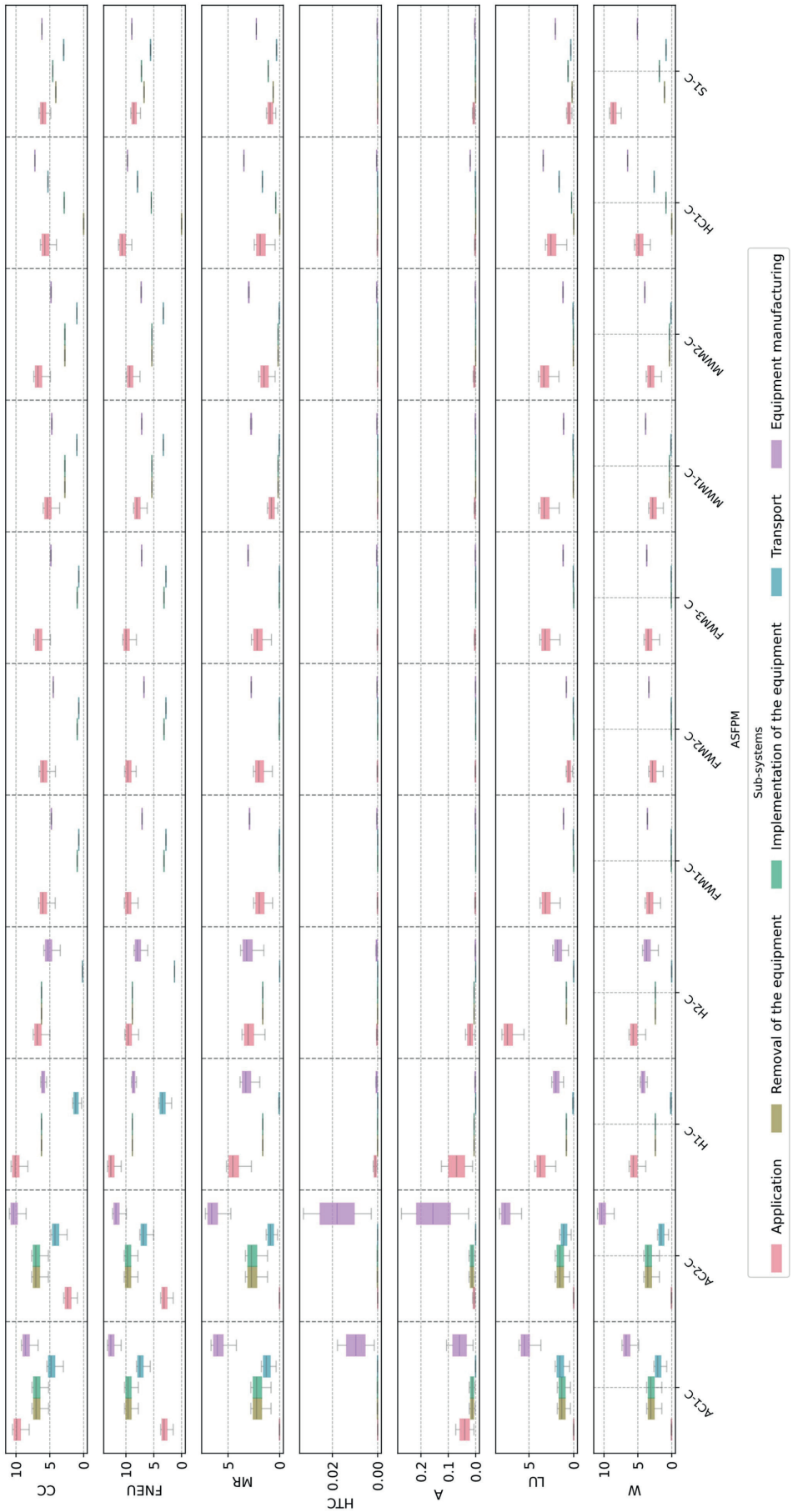


FIGURE 4. Comparison of the sub-system impact's variation for all ASFPMs of the Champagne region through the selected LCA indicators.

CC: Climate change short term in kg of CO_2 eq. FNEU: Fossil and nuclear energy use in MJ deprived. MR: Mineral resources use in kg deprived. HTC: Human toxicity cancer in CTUh. A: Terrestrial acidification in kg of SO_2 eq. LU: Land occupation biodiversity in m^2/yr arable. W: Water scarcity in m^3 world eq. The y-axis represents the indicator score in log (1 + specific indicator value) per type of ASFPM technology. AC1-C: antifrost candles, champagne region, petrol as raw material. AC2-C: antifrost candles, champagne region, palm oil as raw material. FWM1-C: wind machine, Champagne region, fixed machine, gas fuel, with small heaters. FWM2-C: wind machine, Champagne region, fixed machine, gas fuel, without small heaters. FWM3-C: wind machine, Champagne region, fixed machine, gas fuel, with burner. MWM1-C: wind machine, Champagne region, mobile machine, diesel fuel, with a small heater. MWM2-C: wind machine, Champagne region, mobile machine, diesel fuel, with burner. H1-C: heater, Champagne region, fuel as an energy resource. H2-C: heater, Champagne region, wood as an energy resource. HC1-C: heating cable, Champagne region, copper cable. S1-C: sprinkler, Champagne region, 50 m^3 of direct water consumption.

		CC	FNEU	MR	HTC	A	LU	W
Antifrost candle	*AC1-C*	2.6E+04	3.4E+05	4.1E+02	9.2E-03	1.2E-01	2.3E+02	8.2E+02
	AC2-C	3.2E+04	1.5E+05	7.0E+02	1.7E-02	1.9E-01	2.0E+03	2.9E+04
	AC1-V	1.5E+04	2.0E+05	2.4E+02	5.4E-03	7.0E-02	1.6E+02	4.9E+02
Wind machine	*FWM1-C*	5.1E+02	1.6E+04	2.3E+01	3.8E-04	2.4E-03	2.3E+01	6.0E+01
	FWM2-C	4.7E+02	1.5E+04	2.1E+01	3.4E-04	1.4E-03	2.0E+00	4.3E+01
	FWM3-C	9.2E+02	2.1E+04	2.8E+01	4.6E-04	3.6E-03	2.4E+01	6.8E+01
	MWM1-C	3.4E+02	4.6E+03	1.6E+01	3.1E-04	4.2E-03	2.6E+01	6.2E+01
	MWM2-C	9.5E+02	1.2E+04	2.3E+01	4.2E-04	6.0E-03	2.8E+01	7.4E+01
	FWM1-V	6.4E+02	8.4E+03	1.6E+01	2.7E-04	7.5E-03	2.8E+01	5.3E+01
	FWM2-V	4.4E+02	1.4E+04	1.9E+01	3.0E-04	2.1E-03	2.0E+01	4.9E+01
	FWM3-V	5.9E+02	7.6E+03	1.3E+01	2.3E-04	6.4E-03	3.2E+00	3.4E+01
	FWM4-V	1.0E+03	1.3E+04	1.9E+01	3.2E-04	8.9E-03	3.1E+01	5.7E+01
	MWM1-V	4.5E+02	6.1E+03	1.9E+01	3.7E-04	5.6E-03	3.1E+01	6.1E+01
	MWM2-V	8.2E+02	1.1E+04	2.2E+01	3.9E-04	1.0E-02	3.4E+01	5.9E+01
Heater	*H1-C*	2.4E+04	3.2E+05	1.2E+02	1.5E-03	8.1E-02	4.7E+01	3.6E+02
	H2-C	2.1E+03	3.0E+04	4.9E+01	7.1E-04	3.2E-02	1.5E+03	3.3E+02
	H1-V	2.5E+04	3.3E+05	1.2E+02	1.5E-03	8.1E-02	4.7E+01	3.6E+02
	H2-V	2.1E+03	3.0E+04	4.9E+01	7.2E-04	3.2E-02	1.6E+03	3.3E+02
	H3-V	1.4E+04	5.1E+04	4.4E+01	7.5E-04	7.9E-02	1.8E+01	1.6E+02
Heating Cable	*HC1-C*	1.8E+03	6.0E+04	4.1E+01	5.7E-04	2.3E-02	4.4E+01	8.0E+02
	HC1-V	1.0E+03	4.3E+04	2.1E+01	3.0E-04	1.3E-02	2.4E+01	5.6E+02
	HC2-V	3.2E+03	7.1E+04	4.4E+01	6.3E-04	3.2E-02	6.0E+01	1.1E+03
Sprinkler	*S1-C*	1.0E+03	1.5E+04	1.3E+01	2.4E-04	1.1E-02	8.9E+00	5.6E+03
	S1-V	1.2E+03	1.7E+04	1.4E+01	2.9E-04	1.3E-02	1.0E+01	4.8E+03
Winter Cover	WC1-V	2.3E+03	3.1E+04	3.2E+01	6.9E-04	1.0E-02	3.3E+01	6.7E+02

FIGURE 5. Comparison of ASFPMs for 11 hours of frost within the ASFPM's technologies between optional alternatives and the territory of application.

FU: to protect 1 ha for 11 hours of frost, except for WC1-V which is to protect 1ha with 11 fold and unfold operations. CC: Climate change short term in kg of CO_2 eq. FNEU: Fossil and nuclear energy use in MJ deprived. MR: Mineral resources use in kg deprived. HTC: Human toxicity cancer in CTUh. A: Terrestrial acidification in kg of SO_2 eq. LU: Land occupation biodiversity in m^2/yr arable. W: Water scarcity in m^3 world eq. The environmental scores are in absolute values. Darker colours represent higher scores within the indicator category and type of technology. Each colour corresponds to a type of ASFPM technology. AC1-C: antifrost candles, champagne region, petrol as raw material. AC2-C: antifrost candles, champagne region, palm oil as raw material. AC1-V: antifrost candles, Loire Valley region, petrol as raw material. FWM1-C: wind machine, Champagne region, fixed machine, gas fuel, with small heaters. FWM2-C: wind machine, Champagne region, fixed machine, gas fuel, without small heaters. FWM3-C: wind machine, Champagne region, fixed machine, gas fuel, with burner. MWM1-C: wind machine, Champagne region, mobile machine, diesel fuel, with a small heater. MWM2-C: wind machine, Champagne region, mobile machine, diesel fuel, with burner. FWM1-V: wind machine, Loire Valley region, fixed machine, diesel fuel, with small heaters. FWM2-V: wind machine, Loire Valley region, fixed, gas fuel, with small heaters. FWM3-V: wind machine, Loire Valley region, fixed, diesel fuel, without small heaters. FWM4-V: wind machine, Loire Valley region, fixed, diesel fuel, with burner. MWM1-V: wind machine, Loire Valley region, mobile, diesel fuel, with small heater and generator. MWM2-V: wind machine, Loire Valley region, mobile, diesel fuel, with a small heater. H1-C: heater, Champagne region, fuel as an energy resource. H2-C: heater, Champagne region, wood as an energy resource. H1-V: heater, Loire Valley region, fuel as an energy resource. H2-V: heater, Loire Valley region, uses wood as an energy resource. H3-V: heater, Loire Valley region, uses peat as an energy resource. HC1-C: heating cable, Champagne region, copper cable. HC1-V: heating cable, Loire Valley region, copper cable. HC2-V: heating cable, Loire Valley region, radiative cable with diode. S1-C: sprinkler, Champagne region, 50 m^3 of direct water consumption. S1-V: sprinkler, Loire Valley region, 35 m^3 of direct water consumption. WC1-V: winter cover, Loire Valley region, non-woven polypropylene cover.

the plastic pipes manufacturing, AC2-C due to the production of oil palm and HC1-C due to the cable manufacturing.

For the Fossil and nuclear energy use indicator, the equipment manufacturing sub-system is the largest contributor for AC1-C and AC2-C mainly due to the paraffin production and S1-C mainly due to the manufacturing of aluminium poles. For the same indicator, the application sub-system is the largest contributor for all other ASPMs regardless of frost occurrence due to the production of fuel resources.

For the Mineral resources use indicator, the equipment manufacturing sub-system is the largest contributor for all ASFPMs, except for H1-C where it is the application sub-system due to the extraction and production of light fuel oil, regardless of frost occurrence.

For the Human toxicity cancer indicator, the equipment manufacturing sub-system is the largest contributor for all ASFPMs, except for H1-C where it is its application sub-system due to the extraction and production of light fuel oil.

For the Terrestrial acidification indicator, the application subsystem is the most impactful sub-system for H1-C, H2-C, FWM1-C, FWM2-C, FWM3-C, MWM1-C, MWM2-C and S1-C regardless of frost occurrence mainly driven by the combustion of fuel resources. For AC1-C, AC2-C and HC1-C, the equipment manufacturing sub-system is the largest contributor regardless of frost occurrence due to the production of paraffins and the waste treatment of the electric cables, respectively.

For the Land occupation indicator, the largest contributor is the equipment manufacturing sub-system for AC1-C and AC2-C due to the paraffin production, FWM2-C due to the metallic infrastructure, HC1-C due to the manufacturing and disposal of the cables and S1-C due to the manufacturing of aluminium poles. The application sub-system is the largest contributor regardless of frost occurrence for H1-C and H2-C due to the production of fuel resources, FWM1-C, FWM3-C, MWM1-C and MWM2-C due to the wood production for small heaters or burner use.

For the Water scarcity indicator, the largest contributor is the equipment manufacturing sub-system regardless of frost occurrence for AC1-C and AC2-C due to the paraffin production; FWM1-C, FWM2-C, FWM3-C, MWM1-C and MWM2-C due to the glass or carbon fibre blades and the metallic tower manufacturing and HC1-C due to the cable manufacturing and disposal. For S1-C, H1-C and H2-C, the application sub-system is the main contributor due to direct water consumption, light fuel and wood pellet production.

The main source of variability in all environmental categories of AC1-C, AC2-C, H1-C and H2-C can be explained by the equipment manufacturing and the application sub-systems as their quantity depends on the frost hours occurring. The transport subsystem influences the Climate change, Fossil and nuclear energy use, Mineral resources use, Land occupation and Water scarcity indicators for AC1-C, AC2-C and H1-C as more transport is required if the frost hours increase. The application sub-system is the main source of variability in all indicators for FWM1-C, FWM2-C, FWM3-C, MWM1-C, MWM2-C, HC1-C and S1-C due to their increasing demand in fuel resources or electricity if frost hours increase, except for the Human toxicity cancer indicator. Concerning AC1-C and AC2-C, the removal and implementation equipment subsystems contribute to the variability across all environmental indicators, except for the Human toxicity cancer indicator. This can be explained as they are instant practices dependent on the frost occurrence in terms of installation and removal actions.

In both Loire Valley and Champagne regions, the application sub-system contributes the most to the variability across most impact categories for ASFPMs based on fixed infrastructure, such as wind machines or sprinklers. In contrast, for ephemeral ASFPMs, such as candles or heaters, the environmental impacts are more strongly influenced by the manufacturing of the equipment, which is closely tied to the frequency of frost events.

3. Comparison of ASFPM's environmental performances between territories

Figure 5 compares the environmental performance of the Loire Valley and Champagne ASFPMs for each environmental category with the following FU: "To protect 1 hectare for 11 h of frost", except for the WC1-V which is "to protect 1 hectare with 11 fold and unfold operations". The absolute values are presented for each indicator and the different ASFMs are compared within the same ASFPM technology (a darker colour refers to a higher impact within the technology). For the antifrost candle technology, AC2-C has the highest environmental score for all indicators, except for the fossil and nuclear energy use indicator, where AC1-C has the highest score. This difference is mainly due to the impact of the palm-oil-based paraffin production which is higher than the petrol-based paraffin. For the wind machine technology, The FWM4-V has the highest impact on Climate change due to the use of an additional burner consuming a high quantity of fuel resources. For the Fossil and nuclear energy use, Mineral resources use and Human toxicity cancer indicators, FWM3-C has the highest impact due to the use of a burner, involving a high consumption of natural gas and a complex infrastructure. The MWM2-C has the highest impact on the Water scarcity indicator due to the use of a burner, involving a complex infrastructure and a reduced protected area compared to the fixed wind machines. The MWM2-V has the highest impact on the Terrestrial acidification and Land occupation indicators due to a high consumption of fuel resources and a reduced protected area compared to the other wind machines. For the technology of heaters, the H1-V is the most impacting, closely followed by the H1-C, for all environmental indicators due to the use of light oil fuel as fuel resources, except for the Land occupation indicator. H2-V is the most impactful for the Land occupation indicator due to the use of wood as a fuel resource, closely followed by H2-C. H3-V is more impactful than H2-C and H2-V for all indicators due to the peat production except for the Mineral resources use, Land occupation and Water scarcity indicators. For the heating cable technology, HC2-V has

the highest impact on all indicators as the diode production and disposal are more impacting than the other electric cables. Then, HC1-C has a higher impact than HC1-V for all environmental indicators due to the plantation density in the Champagne region, involving more equipment per hectare. Finally, S1-C has a higher consumption of water, explaining its higher impact on the Water scarcity indicator. However, S1-V has higher impacts on the other indicators due to higher equipment needs, specifically due to the aluminium production for the sprinklers. The differences between the environmental scores of the ASFPMs from the two territories are not directly linked to external factors, except for the heating cables HC1-V and HC1-C.

4. Uncertainty and sensitivity analyses

The uncertainties of the environmental indicators of ASFPMs for each of the seven indicators can be found in the supplementary material provided. These uncertainties are based on the quality scores of the data, provided by the Ecoinvent and Agribalyse databases and the uncertainty data of the Impact World + characterisation methodology. For the ASFPM unit processes, there are no uncertainty inputs as the data come directly from interviews conducted in the Loire Valley and Champagne regions.

Among the indicators assessed, water scarcity has the highest relative uncertainty, due to its high coefficient of variation in all ASFPMs. The exceptions are for WC1-V, H2-V and H2-C, the winter cover and the wood-burning heaters, where human toxicity (cancer) has the highest coefficient of variation due to the high amount of plastic production and disposal and the wood production uncertainties. In contrast, Fossil and nuclear energy use and Climate change indicators have the lowest uncertainty across all ASFPMs.

Overall, the absolute uncertainties are relatively low for all environmental indicators, except for the Water scarcity indicator in all ASFPM results and the Human toxicity cancer indicator for the winter cover and wood-burning heaters.

Regarding the sensitivity analysis of characterisation methodologies, the EF results from the ASFPM comparison can be retrieved in the supplementary material. Overall, the EF results align with the Impact World+ indicators, except for the Resource Use (mineral and metal) indicator. In this category, radiative and heating cables show the highest impacts, regardless of frost occurrence in the Loire Valley region and when frost hours are below 22 in Champagne. This discrepancy arises because the EF Resource Use (mineral and metal) indicator, expressed in kg of Sb deprived, does not account for the same substances as the Mineral Resource Use indicator in Impact World +. The primary contributor to the EF Resource Use (mineral and metal) impact is copper cables, similar to the Mineral Resource Use indicator in Impact World+. However, the two indicators respond differently to frost hour variations, as the Mineral Resource Use indicator also includes contributions from electricity consumption, which is not considered in the EF Resource Use (mineral and metal) indicator. For the Human Toxicity Cancer indicator, sprinklers have the highest impact when frost hours are low, particularly in the Loire Valley region. However, as frost hours increase, antifrost candles become the dominant contributor in both territories. The main source of impact for this indicator in EF is the waste treatment of the polyvinylchloride pipes, especially due to the incineration processes which does not contribute to the same extent in the indicator of Impact World +.

DISCUSSION

This case study compares the environmental scores of six different ASFPM technologies within a context-specific LCA framework from Baillet *et al*. (2024b). The framework allows for comparing the environmental impacts of ASFPMs while including contextual elements such as microclimate, plantation density and decisional factors. The environmental performance of these technologies is evaluated based on seven environmental indicators in two French regions: the Loire Valley and Champagne. By considering both regions, this case study captures differences in climatic conditions and plantation densities, providing a more nuanced analysis of the environmental impacts of ASFPM technologies. The scenarios of application only vary in the types of ASFPM technology used.

For each environmental indicator, a ranking of the environmental scores for ASFPMs was established in both regions. In both the Loire Valley and Champagne, wind machines consistently had the lowest environmental scores across all the indicators from 1 hour of frost per spring, except for Mineral resources use, where sprinklers had the lowest score in Champagne. In the Loire Valley, heating cables using radiative technology exhibited the highest environmental scores for Climate change, Fossil and nuclear energy use, Terrestrial acidification, Mineral resources use and Water scarcity indicators when frost hours were low. Moreover, Winter cover contributed the most to the Human toxicity cancer indicator when frost hours were low. However, as the number of frost hours increased, the hierarchy changed. In this case, fuel-fired heaters had the highest scores for Climate change, Fossil and nuclear energy use and Terrestrial acidification while antifrost candles showed the highest scores for Mineral resources use and Human toxicity cancer indicators. For the Land occupation indicator, wood-burning heaters consistently had the highest score, regardless of the number of frost hours. For the Water scarcity indicator, sprinklers had the highest score from 1 hour of frost in both regions. In the Champagne region, antifrost candles based on palm oil paraffin consistently had the highest score across all environmental indicators, except for Fossil and nuclear energy use, regardless of the number of frost hours. In that case, fuel-fired heaters had the highest score when frost hours were fewer than six. Once frost hours exceeded this threshold, the highest score for this indicator was associated with antifrost candles based on petrol paraffin. Overall, in both regions, wind machines and sprinklers demonstrated more favourable environmental scores, especially when frost occurrences were high. The sensitivity analysis based on EF reinforces the environmental

comparison of ASFPM, as the patterns and rankings remain consistent across all environmental indicators, except for Human Toxicity Cancer and Resource Use (mineral and metal). In these cases, sprinklers exhibit higher scores when frost occurrence is low, while heating cables have the highest impacts in the Resource Use (mineral and metal) category.

For each environmental indicator, the main sources of score variability and the key contributors were identified for each ASFPM in both regions. In both the Loire Valley and Champagne, the direct application sub-system was the main source of variability for all ASFPMs from the heating category, as defined by Rochard *et al*. (2019). This is because the consumption of fuel resources is directly proportional to the number of frost hours. Instant solutions, such as antifrost candles and heaters, showed greater variability across all sub-systems in the LCA model, particularly in the equipment manufacturing and transport sub-systems. In contrast, the winter cover showed low variability, with the only source of variability coming from the equipment implementation sub-system. Since no resource consumption is needed for its direct application in the field, the impact of this technology remains relatively constant across the studied contextual elements.

The comparison of environmental scores for ASFPMs across the two regions and within the same technology did not reveal a clear trend for a given amount of frost hours. The difference in plantation density, which varies from 5000 vines per hectare in the Loire Valley to 10,000 vines in Champagne, influenced the equipment manufacturing sub-system for the heating cable technology. This resulted in a higher environmental impact for the heating cables in the Champagne region. Additionally, more antifrost candles per hectare are used in Champagne compared to the Loire Valley, leading to a higher environmental impact across all sub-systems for each indicator. Sprinklers in Champagne also require a higher water consumption per hectare due to a stronger pressure flow, resulting in higher impacts on the Water scarcity indicator. The fixed wind machines in the Champagne region had a lower impact on Climate change than those in the Loire Valley because they use natural gas instead of diesel as a fuel source. However, when the same fuel type is used, wind machines in the Loire Valley showed lower environmental scores across all indicators, which can be attributed to the higher density of wind machines per hectare in Champagne. Significant differences were observed when comparing the environmental scores of ASFPMs for the same millesimal year. For instance, the ASFPMs from the Champagne region showed higher environmental impacts due to a greater occurrence of frost in 2021. The LCA study of ASFPMs in two contrasting French wine regions enabled the identification of key contextual elements influencing environmental indicators. It also helped refine LCA assumptions and data, thereby increasing the reliability of the insights.

In the study by Pauthier *et al*. (2022), the carbon footprints of seven ASFPMs were compared using similar system boundaries and functional units as in our study. Interestingly, the environmental performances of the aspersion showed better results than wind machines on the Climate change indicator, which contrasts with the findings of the present study. Additionally, Pauthier *et al*. (2022) found that heating cables were as impactful as wind machines in terms of kg CO_2 equivalent per hectare, which is not the case in the present study. However, the hierarchy between fuel-fired heaters and antifrost candles in the study of Pauthier *et al*. (2022) aligns with the findings of this case study. Milà i Canals *et al*. (2006), performed LCAs on apple production in two contrasting regions, where frost protection practices were one of the major differentiating factors. Their study assessed the use of sprinklers and wind machines and showed that these technologies contributed significantly, up to 20 %, to the total energy consumption of apple production per hectare. A significant variation in these contributions was observed between the regions, which is consistent with the results of the present study. However, absolute values for comparison with this study were not provided in Milà i Canals *et al*. (2006) and Pauthier *et al*. (2022). According to the review by Ferrara and De Feo (2018), fossil fuel consumption by agricultural machinery is one of the key factors driving high environmental impacts in the viticulture stage of the wine life cycle. The present study demonstrates that ASFPMs could significantly contribute to the environmental performance of this stage. For instance, the Climate change indicator ranges from 154 to 5294 kg CO_2 equivalent per hectare during minimal frost hours and between 539 to 62,700 kg CO_2 equivalent per hectare during maximum frost hours. In the study by Renaud-Gentié (2015), the viticulture stage accounted for between 1290 and 1720 kg CO_2 equivalent per hectare during the 2021 production year. These findings highlight that the environmental impacts of ASFPMs are far from negligible, even for the most sustainable solution.

For future research, it would be valuable to integrate ASFPMs into the Pathway of Technical Operations (PTO) of the viticulture stage. PTOs represent the overall technical operations carried out during a given year of grape production (Renaud-Gentié *et al.,* 2014). Incorporating the environmental performance of ASFPMs alongside the other viticulture would allow for a more comprehensive assessment of their contributions to the wine production cycle. A sensitivity analysis could also be conducted to assess how the environmental impacts of ASFPMs vary according to context-specific factors, such as microclimate and vineyard conditions. Additionally, it would be relevant to analyse whether environmental compensation occurs when comparing PTOs with and without ASFPMs, particularly in relation to yield loss variation in a given year of grape production. To achieve this, efficiency scenarios could be developed to simulate the yield saved by using ASFPMs under the influence of different contextual factors, such as the type of ASFPMs, frost severity, frost duration, budburst period and other relevant elements.

Moreover, the different ASFPMs studied could lead to consequences that necessitate additional technical operations

that should be taken into account in the PTO. For example, increased water input from the use of sprinklers might require the application of specific phytosanitary products, while the installation of certain ASFPMs could demand supplementary soil management practices.

Simulating the vine phenological changes in conjunction with global warming scenarios would also be valuable, as the projected increase in frost risk is expected to affect several wine-producing regions shortly (Santos *et al.,* 2020; Viveros Santos *et al.,* 2023). This approach would be particularly interesting for examining the impact of cultivating different grape varieties, as their budbreak periods vary, making them more or less susceptible to frost damage (Neethling *et al.,* 2017).

In this study, spring frosts were calculated from early April to late May, as the budburst typically starts at the beginning of April in both territories. However, if budburst occurs earlier due to mild winter and the sensitivity of certain grape varieties, annual spring frost may be underestimated in both regions. Therefore, including March in the analysis could provide valuable insights into the effects of climate change on the potential environmental impacts of ASFPMs. Moreover, frost severity was not accounted for in the modelling of the ASFPM application, which could further lead to an underestimation of ASFPM use. Additionally, the climatic data from the two stations were measured at 2 meters above the ground which likely underestimates the number of frost hours, particularly in radiative frost conditions due to the negative vertical thermal profile (de Rességuier *et al.,* 2023). Moreover, spring frost events are highly specific to individual plot locations and can vary based on the topography and other landscape features. For instance, in the Loire Valley during spring 2021, temperature sensors placed at bud level recorded approximately 13 frost events, with up to 7 hours below 0 °C for a few events (Gastaldi *et al.,* 2021). This underestimation must be acknowledged when analysing the contribution of ASFPMs in the environmental performance of the viticulture stage.

However, despite this limitation, a clear trend emerges in the context-specific and comparative LCA of ASFPMs, as the hierarchy of their environmental performance quickly stabilises. Uncertainties are often considered as a limit in comparative LCA (Ross *et al.,* 2002). The context-specific LCA introduces additional complexity due to the integration of more assumptions, which increases uncertainty. However, as consequential LCA aims to do (Brandão *et al.,* 2014), the context-specific LCA of ASFPMs provide results that, while less precise, are more accurate of real-world scenarios than those that could be from attributional LCA. Nonetheless, future research could benefit from identifying guidelines to better handle uncertainties within the framework of Baillet *et al*. (2024b). This would improve the reliability of LCA as a tool for decision-making support in environmental assessment.

CONCLUSION

This case study highlighted the environmental impacts of using ASFPMs to protect vineyards. It presented a comprehensive comparison of the most used ASFPMs in France, emphasising their potential environmental performance ranking and key sources of environmental impact. Significant differences in the environmental performance of ASFPMs were observed through the context-specific LCA, underscoring the importance of considering contextual elements when comparing technologies with a common function. In the overall environmental assessment, wind machines exhibited the lowest environmental impacts, closely followed by sprinklers, in both the Loire Valley and Champagne regions. In contrast, instant ASFPMs, such as heaters and anti-frost candles, demonstrated the highest environmental impacts for most indicators in both regions. These technologies also showed the greatest variability in relation to frost hour. On the other hand, permanent ASFPMs, particularly those that do not rely on fuel combustion, exhibited the lowest variability in the sensitivity analysis, highlighting their potential relevance when used in high-risk areas for spring frost. This analysis contributes to a deeper understanding of the overall environmental impact of wine production, particularly in regions facing extreme events and serves as a first step to integrate exceptional practices in the viticulture stage. Future research could integrate this analysis into the broader LCA of the viticulture stage to quantify its contribution and explore more efficient usage scenarios, such as the application of passive spring frost protection methods including preventive and agronomic practices. This would enable a more refined assessment of the effects of climate change on ASFPMs and could be extended to other areas, such as economic or social analyses, to provide a more comprehensive and sustainable evaluation of viticulture practices.

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