

Article

Comparing Innovative Versus Conventional Ham Processes via Environmental Life Cycle Assessment Supplemented with the Assessment of Nitrite Impacts on Human Health

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Featured Application: Both methodological in developing LCA with human health indicators and applied in highlighting the interests of high-pressure technologies on the one hand and alternatives to nitrites in ham on the other hand.

Abstract: Global sustainability indicators, particularly in human health, are necessary to describe agrifood products footprint. Nitrosamines are toxic molecules that are often encountered in cured and processed meats. As they are frequently consumed, meat-based products need to be assessed to evaluate their potential impact on human health. This article provides a methodological framework based on life cycle assessment for comparing meat product processing scenarios. The respective contributions of each step of the product life cycle are extended with a new human health indicator, nitrosamine toxicity, which has not been previously included in life cycle assessment (LCA) studies and tools (software and databases). This inclusion allows for the comparison of conventional versus innovative processes. Nitrosamines toxicity was estimated to be 2.20×10^{-6} disability-adjusted life years (DALY) for 1 kg of consumed conventional cooked ham while 4.54×10^{-7} DALY for 1 kg of consumed innovative cooked ham. The potential carcinogenic and noncarcinogenic effects of nitrosamines from meat products on human health are taken into account. Human health indicators are an important step forward in the comprehensive application of LCA methodology to improve the global sustainability of food systems.

Keywords: life cycle assessment (LCA); nitrosamines; nitrites; meat product; innovative process



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1. Introduction

1.1. Sustainability Impact Assessment in the Agrifood Industry and Meat Sector

Food accounts for 20% to 30% of the environmental impact of total household consumption in the European Union and could contribute more than 50% of some impact categories, such as the acidification impact category. Meat products are partly responsible for this high environmental impact [1]. Pork (fresh meat and sausage) was still the most consumed meat in 2015 worldwide, with a consumption rate of 15.3 kg/per year in carcass equivalents, representing approximately 37% of the total meat consumption [2]. Pork offers a wide variety of products at a low price and is fairly stable, and 34% of meat product volumes were purchased in a processed form [3]. Ham production has, therefore, significant impacts on human health and the environment.

Much work has been done on the environmental assessment of meat production through life cycle assessment (LCA) studies. For example, in a Weidema study [4], household storage accounted for 20% of the total energy consumption in the life cycle of meat products. Calderon et al. [5] identified transportation as a second priority step in the

environmental impact of canned pork. According to Davis and Sonnesson [6], reducing the environmental impact of eating a poultry-meat-based meal is as important as improving the environmental performance of manufacturing a ready-to-eat product. Some improvements have been proposed in three aspects of the life cycle of meat products: utilization (reducing food waste transportation), agricultural steps (reducing water use and emissions to the environment, as well as land use), and energy consumption (reducing agricultural consumption, food processing, distribution, and household consumption) [4].

However, most studies still stop at the farm gate [7–9]. Life cycle steps occurring before the farm gate (livestock feed and animal husbandry) are mainly responsible for the total environmental impact, with over 80% contribution to acidification and eutrophication and 60% to 80% contribution to greenhouse gas emissions [4,10–13]. The life cycle steps after the farm gate (slaughter, production, distribution, and consumption) account for 10% to 40% of greenhouse gas emissions and 10% to 70% of energy consumption, with a very small contribution to acidification and eutrophication impacts [4,6,7,10–12,14–18]. On the other hand, water depletion has been recently included in LCA studies of meat products as an impact category. The contribution of the post-farm steps to this category is 15–36% [19–21], depending on the species; for example, the contribution of the post-farm steps to the carbon footprint of packaged fresh beef is negligible [22].

The contribution of life cycle steps to the global impact of the product is then influenced by the specific characteristics of the meat (species, energy sources, type of processing, packaging, storage, transport, and consumption mode) and the methodological choices of the studies (system limits, type of allocation, and assumptions). These conditions prevent the comparison of environmental impacts between products. Other discriminating indicators are still needed to better characterize and compare the sustainability of products. This is why this study focuses on a human health indicator, based on nitrosamines from nitrites in ham. Those substances have been selected because they are largely discussed in the literature [23].

1.2. Human Health Footprint: The Case of Nitrosamines in Ham Production

Meat products may contain nitrites that are used for their technological role (color and oxidation prevention), sensory attributes, and preservation of those products. Nitrites are precursors of nitrosamines: nitrosamines are formed from the reaction between nitrites and amino acids or secondary amines. Nitrosamines are molecules with known toxicity, especially their carcinogenic effects. In the environment, the main sources of nitrosamines are food, cigarettes, and occupational activities (rubber manufacturing), and they are thus pollutants of water sources [24,25]. Indeed, an exposure pathway is the consumption of meat products [26]. This is why the authorized amount of sodium nitrite in meat products is regulated and limited to a maximum of 150 mg.kg⁻¹ product [27] by the European Food Safety Authority (EFSA).

The nitrosamines most commonly found in the meat matrix are N-nitrosodimethylamine (NDMA), N-nitrosodiethylamine (NDEA), N-nitrosopiperidine (NPIP), and N-nitrosopyrrolidine (NPYR) [28]. Among these substances, NDMA and NDEA are recognized as probable carcinogens by the International Agency for Research on Cancer (IARC) [29–31]. NPIPs and NPIYRs also have the potential to pose cancer risks. However, some agents, such as ascorbic acid and alpha-tocopherol, influence the reaction and decrease the formation of nitrosamines.

Daily consumption of nitrites may increase the risk of gastrointestinal cancer due to the *in vivo* formation of nitrosamines. The endogenous formation of N-nitroso compounds in the stomach is complex and depends on several factors, such as gastric pH, bacteria, and the presence of antioxidants [32]. The amount of those components is therefore very complex to evaluate, model, and predict [33]. In addition, the processing and storage of meat can increase the amount of amines available for nitrosamine formation [34]. Therefore, many alternatives have been developed to limit the use of nitrites in cured and processed

meat products [35]. Figure 1 illustrates the general risks and benefits associated with nitrite treatment of ham and, more generally, of cooked and processed meat products.

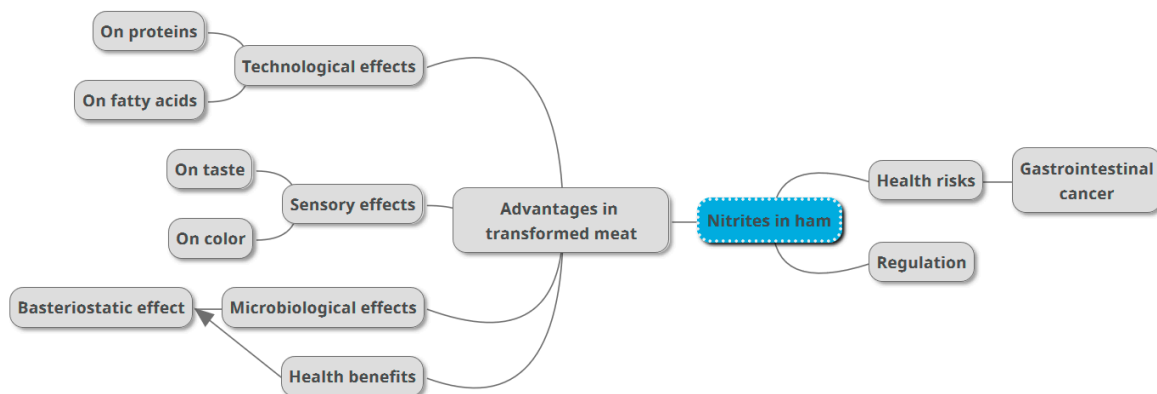


Figure 1. Overview of the risks and benefits associated with nitrite addition to processed meat.

Cooked ham has been widely used as a marker of the exposure of nitroso compounds because it is largely consumed, and thus exposure to nitrosamines could be considered significant [36–39].

1.3. High-Pressure Treatment: A Scenario to Reduce Nitrite Content

Because of the potentially harmful effect of nitrites, new technologies have been developed to decrease or eliminate nitrite contents in meat products. High-pressure treatment represents a promising alternative to the addition of nitrites in ham due to its preservation ability during the life of the product. The resistance of bacteria in the food medium, as well as the recovery of bacterial activity after pasteurization, are two major problems in meat products. It was shown in 1895 that starting from 400 MPa a high-pressure treatment could significantly slow down the growth recovery of microorganisms, such as weathering or pathogenic bacteria. It thus increases the shelf life of the products [40–43]. Deactivation depends on many parameters, such as the type of pathogen, pressure level, process temperature, treatment time, and pH. For example, some studies have shown that a storage temperature lower than 6 °C, combined with a treatment of 600 MPa, can prevent the resumption of growth of *Listeria monocytogenes* in cooked ham [44,45]. High-pressure treatment cannot always replace conventional techniques but may be a complementary treatment that increases the shelf life of meat products. Currently, meat products represent 30% of high-pressure products marketed [46], and high-pressure cooked ham is one of the first products marketed in Europe at the end of the nineteenth century [47].

The addition of a high-pressure operating unit in ham production could have an effect on the environmental impact of the final product and especially on human health consequences. Therefore it seemed important to discriminate between the different processes and to evaluate the environmental and human health impacts of the life cycle of cooked ham. The environmental performance of high-pressure processing technology for food processing was compared with traditionally used food preservation technologies such as thermal pasteurization and modified atmosphere packaging [48]. Based on the methodology of life cycle analysis, involving in particular primary data on the flows and consumption of high-pressure processing (HPP) plants, the evaluation of the environmental performance of sliced Parma ham shows that high-pressure treatment appears to have a lower environmental impact in almost all impact categories than others processes. Indeed, packaging under a modified atmosphere requires a large amount of packaging materials and food gases, and thermal pasteurization a large amount of energy. This study aims to highlight the environmental benefits of high-pressure treatment, a well-known non-thermal technology, but still limited in terms of use. Further studies confirming its low impact on the environment are required and should be supplemented with human health analyzes.

In this article, a combination of two innovative processes was evaluated, high-pressure processing and biopreservation with lactic acid bacteria, as recommended by Simonin et al. [49]. The objectives of this study were the following: (i) comparison of the potential environmental impact of ham production through two different technological paths: conventional production versus production with an innovative process (high pressure + biopreservation); (ii) development of a characterization factor to take into account nitrite contents in the human health impact and to help compare different technological processes.

2. Methods

2.1. Environmental Life Cycle Footprint of Ham Production

Goal and scope: The reference system corresponded to the production of a conventional, superior ham.

Functional unit: The main function of cooked ham is to feed the population by meeting implicit and/or explicit consumer needs. Cooked ham is mainly sold sliced, and the weight of the unit of sale most often purchased is 0.18 kg (or four slices). For our study and to compare alternative systems, all emissions and resources are linked to a reference quantity of product. The functional unit was defined as “1 kg of consumed cooked ham”, i.e., superior ham than that mainly consumed in France, namely free of polyphosphates like in Rakotondramavo et al. [50].

System boundaries: The system boundary determination was based on the methodology presented by Hospido et al. [51]. The following four steps were modeled: raw material production, cooked ham production, distribution, and use phase (consumption). The raw material production stage included conventional breeding (birth, postweaning, and fattening) of pigs in France. The elements included in the subsystem were energy and water production, livestock infrastructure, and feed production. However, veterinary products, cleaning products, food distribution, power cables, and infrastructure for the production of food were not included. The cooked ham production stage included transportation of live pigs to the slaughterhouse, slaughtering and cutting operations (electrical stunning, scalding, dehairing, buckling, eviscerating, bleeding, and cutting), refrigerated transport to the slaughterhouse ham production plant, and cooked ham production operations (receiving, deboning, brining, molding, baking, cooling, slicing, packaging, storing and transporting the ingredients, and primary packaging). The annual production data at the slaughterhouse are related to the quantity of ham pieces per mass allocation. The transport distance between groups of pork producers from the Brittany region and the slaughterhouse was estimated by weighting according to the regional distribution of production. Slaughter-cutting waste accounts for 15% of the live pig weight [52]. The production plant also produces other meat products. The annual production data at the plant were related to the quantity of cooked ham per mass allocation. This study considered the absence of losses during the production of ham. This study also excluded the manufacture of additives (sodium ascorbate and aromatics) present in the processing of the product as well as their transport because they represent less than 0.1% of the final composition of the product. The infrastructure of the facilities, equipment, packaging used for temporary storage and products used for cleaning the facilities were not included. The influence of combined biopreservation and high-pressure processing was evaluated in terms of the life cycle of cooked ham from data on an industrial scale to assess the human health and environmental impacts of its potential application. In the conventional ham production scenario, an embedded amount of 0.1 g per kilo of nitrites was included. No nitrites were assumed to be used in the innovative scenario. A high-pressure program of 600 MPa for 3 min at room temperature was used in this study (data from Villamonte 2014 [53], and from a confidential report disclosed by Hiperbaric). A spray of 25 mg of commercial lactic starter slurry per kilo of ham was used for the biopreservation of the product. Biopreservation is based on the principle of using natural microbial cultures to avoid food spoilage and increase food security. The ferments, therefore, tend to lengthen the shelf life of food by avoiding product degradation. The cultures of lactic ferments used for ham

are specially developed for food application. The extension of the lifetime associated with this innovative treatment (60 days) is comparable to that associated with the conventional treatment product [54,55]. This process did not alter the rest of the life cycle of the product (distribution or consumption, for example). The distribution stage included transport from the plant's warehouses to the distribution platform, storage on the platform (two days), transport to the supermarket, and storage time (energy consumption) in a display case (linear) at the supermarket (seven days). The infrastructure and packaging for transport and storage were not included. The distribution platform was estimated using the Brunel University study approach [56] and information from a study by Rizet et al. [57]. For point-of-sale storage, estimates were obtained from summer energy evaluation studies of a supermarket in France. Round-trip transport with vehicles subject to the European EURO 4 emission standard was considered. The use phase included transportation from the supermarket to the consumer's home, and storage of the product (seven days) in a type A energy label refrigerator was included. The transport characteristics corresponded to an urban consumer in France from the point of sale. The study assumed 3.15% waste of the product, estimated according to the nature of food and waste in France [58]. The end of life of the packaging waste associated with the consumption of the product was included. The data on the energy consumption of the refrigeration were estimated according to the model of Nielsen et al. [52] for a type A refrigerator. The waste was treated by incineration with energy recovery (52.4%) or by storage (47.6%). The steps included in the limits are shown in Figure 2.

Allocation method: mass allocation.

Inventory of inputs, emissions, and resources: The system was described and modeled with SimaPro 8.5.0.0 software (PRé Sustainability, Amersfoort, The Netherlands) [59]. The life cycle inventory included the flow of materials and energy within the system boundaries, adjusted to 1 kg of consumed cooked ham. The primary data (real) were measured and/or provided by officials of the French pork industry French National Pork Institute (IFIP) and a high-pressure processing equipment company (Hiperbaric in Spain). Secondary data (from databases) were supplemented by the database and bibliography available for the reference technology path. The specifications and modalities of the reference and innovative processes were based on the data obtained from the partners, for example, the high-pressure treatment schedules and the inventory of resources needed to cultivate the preservation fermentation. The data for the raw material production step were collected from the Agribalyse French agricultural products database (version 1.3)—the information obtained on pig slaughtering corresponded to an average French slaughterhouse. The data for cooked ham production were collected from conventional French meat producers. The technological level used in the slaughtering and manufacturing steps was modern or automated, and the site capacities were representative of French production. The generic data originated from the EcoInvent 3.3 database. The energy source was that of France and was acquired from this database. The quality of the related data was categorized into generic (pig breeding, distribution, and use) and specific (slaughter-cutting, production of cooked ham, and high-pressure treatment). This information was temporally representative of current production technologies and consumption habits, and based on available sources: livestock (Agribalyse V1.1 February 2014, ILCD-Quality final note 4,5/5), slaughter-cutting and cooked ham production (from IFIP, 2014), distribution (from Villamonte, 2014 [53]), and use (data from Villamonte, 2014 [53]). To summarize, the flows that change between the different scenarios studied are, on the one hand, those linked to the unitary high-pressure treatment operation (i.e., for a kg of cooked ham, 0.0695 kWh of electricity, 700 kPa of compressed air, and 0.377 L of water), as well as the production flows of the lactic ferment for biopreservation (taken into account in the study of raw materials for the manufacture of the culture medium, liquid nitrogen, in particular for keeping the packaging cold, energy and water required, emissions into the air and water (BOD and COD), reduction of avoided impacts thanks to the spreading of the culture medium after use on land in direct proximity to the production of the ferment).

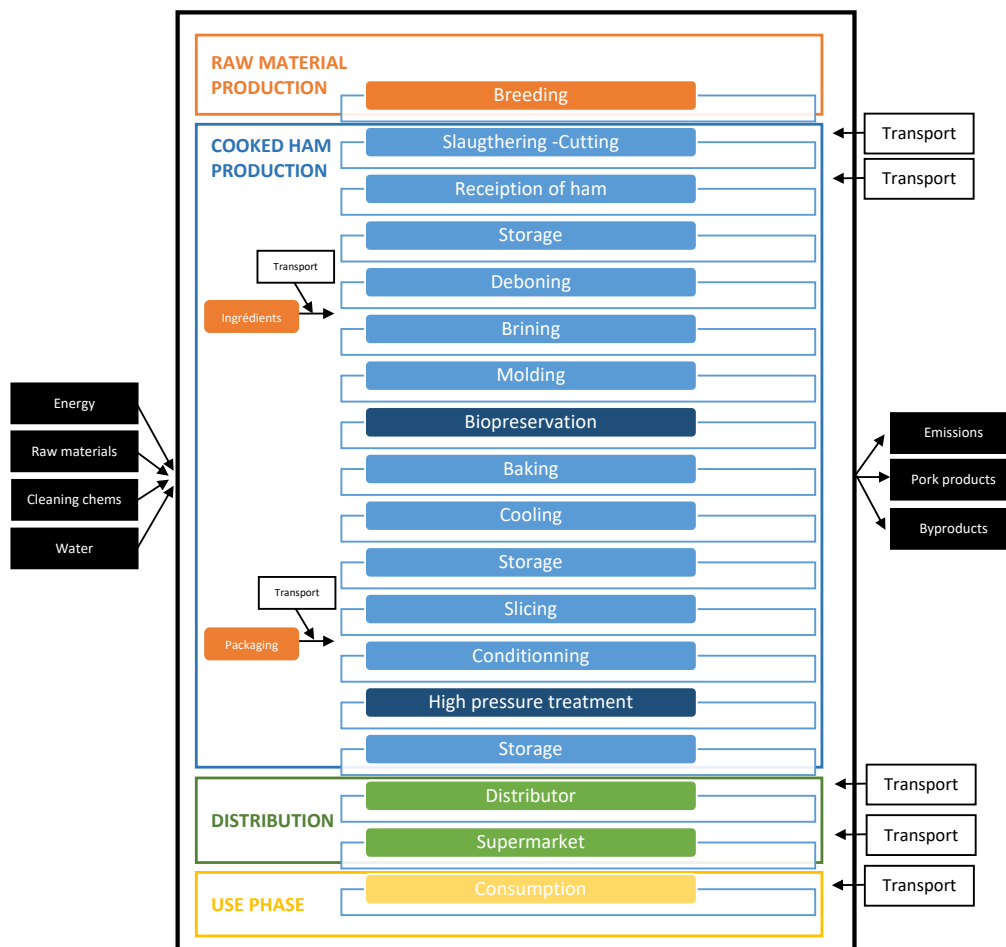


Figure 2. Cooked ham life cycle (brown for raw material, blue for cooked ham production, green for distribution, and orange for consumption).

Impact assessment: All aspects of environmental issues were divided into impact categories. For the food industry, resource use is an essential question in the current context. Therefore, the cumulative demand for renewable and nonrenewable energy, abiotic resource depletion, and water depletion were utilized as impact categories for the study. Reference impact categories, such as climate change, acidification, and eutrophication, were also included. The environmental impact categories were obtained by the ReCiPe method (version 1.12), midpoint (problems), and endpoint (damages, all expressed in DALY for human toxicity). The impact category of water depletion represented only the amount of water used. The cumulative demand for nonrenewable energy was determined by the cumulative energy demand method version 1.09. This method estimated the energy use in the life cycle from renewable and nonrenewable energy resources.

The cumulative demand for energy concerned all renewable and nonrenewable energy sources (nuclear, oil, coal, natural gas, etc.) potentially used throughout the product life cycle. Climate change was evaluated as the concentration of substances, such as carbon monoxide and methane, that disrupt the climate balance and contribute to the greenhouse effect. Metal depletion represents the extraction of mineral resources (ores), expressed in kg of equivalent iron. The indicator for the acidification category was the increase in the concentration of acidifying substances (air pollutants) causing tree dieback, expressed in g of sulfur dioxide (SO₂) equivalents. The eutrophication category, expressed in g of phosphate (P) or nitrogen (N) equivalents, reflected the quantity of nutrients released into the environment that favor the proliferation of certain species and that cause the

disruption of ecosystems. The water-depletion impact category evaluated the total amount of freshwater (m^3) used in the life cycle of cooked ham.

2.2. Human Health Footprint of Ham Production

To take into account the effect of substances in ham, such as nitrites, a new characterization factor was developed to be included in the life cycle assessment in the human health damage category. The methodology for the development of this new characterization factor is described below.

2.2.1. Fate and Exposure

The causal chain of the potential toxicity of nitrosamines via ingestion of meat products containing nitrites is presented in Figure 3. In general, chemical fate includes the transport of the substance through different environmental compartments. The fate factor associates the emissions from a substance in compartment n with the increase of the quantity of the substance in this compartment (air, soil, water, and food) [60]. The particularity of the effect of substances, such as nitrosamines, in foodstuffs, is partly due to the mechanism of food ingestion. In fact, the entire emission (nitrosamines formed in the food) is ingested by the consumer. Thus, the transfer of the substance and its accumulation in another compartment were not taken into account. Indeed, nitrosamines are formed in meat products (exogenous nitrosamines) via the reaction of a nitrosating agent (nitrogen oxides) with amino compounds from proteins. These nitrosating agents are derived from nitrites and favored by heat treatments.

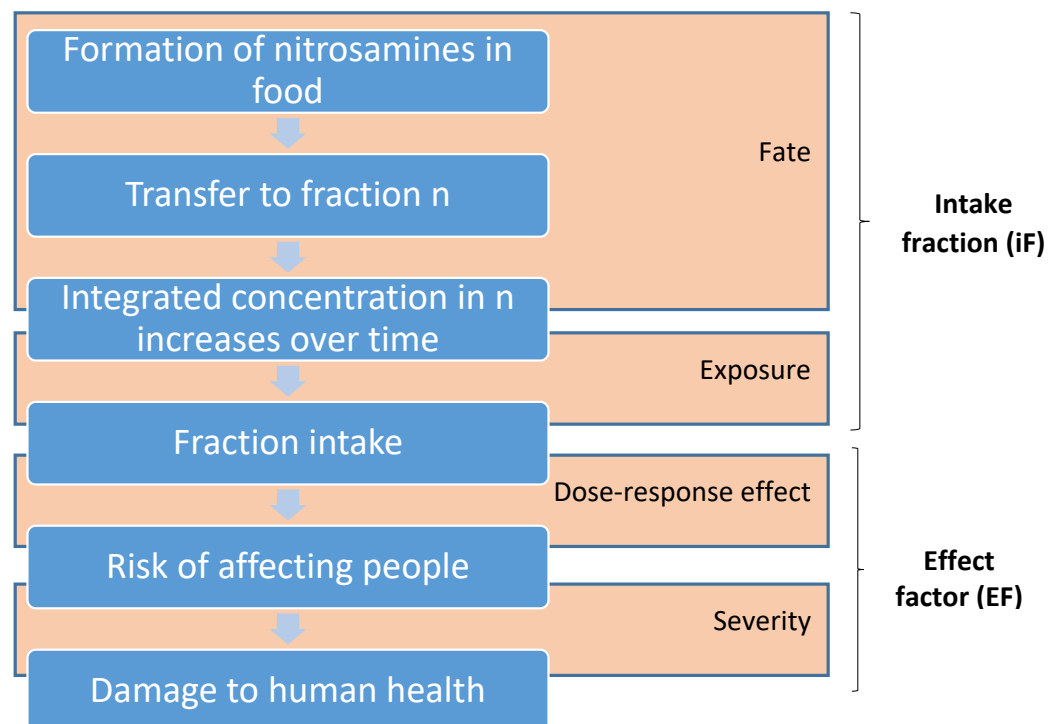


Figure 3. Causality chain of the potential toxicity of nitrosamines via the ingestion of food (inspired by Jolliet et al. 2010 [60]).

Human exposure represents only a fraction of the substance from the food transferred (nitrosamines via the ingestion pathway) to the entire human population. The potential risk to human health was calculated by the probable number of cases per kg of substance ingested by the population. The carcinogenic and noncarcinogenic effects were estimated by toxicity data for the substance from epidemiological studies. The severity of these effects (carcinogenic and noncarcinogenic) was expressed in terms of equivalent life lost

per case of the disease (DALY.cas-1), a unit used by the World Health Organization [60,61]. DALY stands for disability-adjusted life years and is also frequently used precisely in LCA via damage-oriented and/or endpoint methods, which group the impacts according to the results in the cause-and-effect chain and clearly show the impact on a specific category of individuals. The damage factors on human health transform kilograms of the equivalent substance into years of healthy life lost (DALY). For the needs of this study, the French population was considered.

The calculation of the indicator of the potential impact of the toxicity of nitrosamines on humans was defined from the expression established by Udo de Haes [62] for the category of oriented damage to human health (Equation (1))

$$S_i = \sum_i iFi \times EFi \quad (1)$$

where S_i is the impact category indicator (DALY, functional unit⁻¹), F_i is the intake fraction (kg taken functional unit⁻¹), and EFi is the effect factor (DALY, kg taken⁻¹) of the nitrosamine type i . The results are the aggregation of the independent estimate of each nitrosamine compound i in the meat product.

2.2.2. Intake Fraction

The intake fraction of nitrosamine i (iF) is defined as the ingested dose of nitrosamine i per functional unit (FU). The dose considers the concentration of nitrosamine i per unit of food (exogenous nitrosamines). In our study, the fraction of ingested nitrosamines was calculated from Equation (2). The concentration of nitrosamines ($\mu\text{g.kg}^{-1}$) at the time of ingestion was defined by the literature reviews summarized in Table 1. Nitrosamines formed in vivo were not part of the expression.

$$I_i \left(\frac{[\text{nitrosamines taken}]}{FU} \right) = \frac{Nb \text{ doses}}{FU} \times \frac{g_{\text{food unit}}}{\text{dose}} \times \frac{[\text{nitrosamines}]}{g_{\text{food unit}}} \quad (2)$$

Table 1. The concentration of nitrosamines (N-nitrosodimethylamine (NDMA), N-nitrosodiethylamine (NDEA), N-nitrosopyrrolidine (NPYR), and N-nitrosopiperidine (NPIP)) in cooked hams used to estimate the indicator.

Nitrosamines ($\mu\text{g.kg}^{-1}$)	Reference	Nitrosamines ($\mu\text{g.kg}^{-1}$)	Reference
NDMA: 5.09 ± 1.01 NDEA: 4.85 ± 0.54	[63] (reference scenario)	NDMA: 4.9 NDEA: 1.49 NPYR: 5.34 NPIP: 0.04	[28]
NDMA: 11.05 ± 1.2 NDEA: 10.4 ± 0.96	[63] (scenario with polyphosphates)	NDMA: 2 ± 0.3 NDEA: 2.9 ± 0.3 NPYR: 1.8 ± 0.3	[64]
NDMA: 1 NDEA: 0.37 NPYR: 3.73 NPIP: 1.79	[65]	NDMA: 2.18 ± 0.62 NDEA: 0.2 NPYR: 1.75 ± 0.49 NPIP: 0.05 ± 0.02	[66]

2.2.3. Effect and Severity Factor

The USEtox 1.01 model [67,68] was used to calculate the characterization factors. The USEtox characterization model is based on a consensus to address the problems associated with the variability of human toxicity characterization model methodology [69]. UNEP/SETAC (United Nations Environment Programme/Society of Environmental Toxicology and Chemistry) created this model from other models, such as CalTOx, IMPACT 2002 + USES-LCA, BETR, EDIP, WATSON, and Ecosense. The aim was to create a

simple model with a solid scientific basis [69,70] to obtain problem-oriented characterization factors. The fate and exposure factors of the model were modified according to the previously described characteristics. The effect factors of the human toxicity characterization models for nitrosamines from the USEtox analysis were used (Table 2). These factors represented the variation in the probability of disease from the change in nitrosamine uptake over the course of the life of the targeted population. The unit for the potential for human toxicity of nitrosamines was $\text{case}\cdot\text{kg}^{-1}$. The model expresses toxicity in comparative toxic units (CTUs).

Table 2. Factor of the carcinogenic effects of nitrosamines (via ingestion) according to USEtox 1.01 [67,68].

CASE	Nitrosamines	Carcinogenic Effect Factor ($\mu\text{g}\cdot\text{kg}^{-1}$ Intake)
62-75-9	N-nitrosodimethylamine	11.95
55-18-5	N-nitrosodiethylamine	43.25
930-55-2	N-nitrosopiperidine	3.01
100-75-4	N-nitrosopyrrolidine	1.57

The effect factor is based on the extrapolation of ED50 (lethal dose for 50% of a given population). The carcinogenic effects were obtained from the Carcinogenic Potency Database. As the dose-response curve was linear, the EF ($\text{case}\cdot\text{kg}^{-1}$ taken) was calculated according to Equation (3) [67]:

$$EF = \frac{0.5}{ED_{50}} \quad (3)$$

To evaluate the significance of the indicator in relation to other indicators of the damage-oriented impact category of human health from the life cycle analysis of cooked ham, the severity factor for the carcinogenic effect of nitrosamines was considered 11.5 DALY.case-1 according to the study conducted by Huijbregts et al. [71] on carcinogenic chemicals, including nitrosamines.

3. Results and Discussion: Environmental and Human Health Impact Assessment of Cooked Ham Production

3.1. Environmental Life Cycle Assessment of Cooked Ham Production

Table 3 shows the potential environmental impact results of the life cycle of cooked ham production for conventional and innovative scenarios.

Table 3. Environmental and human health impact of the cooked ham life cycle for conventional and combined innovative processes. DALY: disability-adjusted life years.

Impact Category	Units	Conventional Ham	Innovative Ham
Nonrenewable	MJ-Eq	103.003	104.472
Renewable	MJ-Eq	72.429	72.429
Climate change	kg CO ₂ eq	13.422	13.439
Water depletion	m ³	10.958	11.465
Metal depletion	kg Fe eq	0.276	0.277
Terrestrial acidification	kg SO ₂ eq	0.084	0.086
Freshwater eutrophication	kg P eq	0.001	0.001
Marine eutrophication	kg N eq	0.021	0.021
Agricultural land occupation	m ²	5.437	5.438
Human toxicity	kg 1,4-DB eq	0.111	0.112
Nitrosamines toxicity	DALY	2.20x10 ⁻⁶	4.54x10 ⁻⁷

The production of conventionally cooked ham in this study used approximately 103 MJ of nonrenewable energy for the conventional scenario and approximately 104 MJ

of nonrenewable energy for innovative scenarios. For both scenarios, the impact of 63% was fossil energy, and 37% was nuclear energy. Conventionally cooked ham has an impact on greenhouse gas emissions of 13.4 kg CO₂ eq.kg⁻¹ for both scenarios (13.422 for the conventional scenario and 13.439 for the innovative scenario). The conventionally cooked ham induced the depletion of metal resources to the order of 0.28 kg Fe eq.kg⁻¹ of product for both scenarios (0.276 for the conventional scenario and 0.277 for the innovative scenario). The total amount of freshwater (m³) used in the life cycle of cooked ham for both scenarios was around 11 m³ of water (10.958 for the conventional scenario and 11.465 for the innovative scenario).

For all impact indicators except nitrosamine toxicity, the variation between the two scenarios was less than 5%, which is considered negligible. The potential effect of the ham life cycle directly on human health is outlined in part 3.3 Sensitivity analysis. All of these damage-oriented impact categories were then expressed in DALY. Effects on ecosystems were not estimated directly in this study (but could still be calculated from problem-oriented impact categories).

To show how similar the impacts calculated by environmental LCA are for the two scenarios compared, Table 4 presents an analysis of the contributions of the different stages of the product life cycle. This analysis of ham life cycle hotspots shows how the environmental life cycle analysis makes it difficult to distinguish between the two scenarios, conventional and innovative. The production of raw material was the most important step, accounting for 94% of the potential impact due to emissions occurring during pig farming.

Table 4. Hotspots analysis of cooked ham life cycle impacts for conventional and innovative processes.

Impact Category	Unity	Raw Material Production	Production of Cooked Ham		Distribution	Use Phase
			Conventional	Innovative		
Nonrenewable Energy	MJ-Eq	2.81x10 ⁺¹	7.08x10 ⁺¹	7.24x10 ⁺¹	1.98x10 ⁻¹	3.85x10
Renewable energy	MJ-Eq	7.12x10 ⁺¹	1.21x10	1.23x10	0.00x10	8.18x10 ⁻³
Climate change	kg CO ₂ eq	6.22x10	6.86x10	6.89x10	1.36x10 ⁻¹	2.02x10 ⁻¹
Water depletion	m ³	1.50x10	8.71x10	9.22x10	1.57x10 ⁻²	7.29x10 ⁻¹
Metal depletion	kg Fe eq	1.32x10 ⁻¹	1.24x10 ⁻¹	1.26x10 ⁻¹	4.28x10 ⁻⁴	1.93x10 ⁻²
Terrestrial acidification	kg SO ₂ eq	6.90x10 ⁻²	1.46x10 ⁻²	1.69x10 ⁻²	3.04x10 ⁻⁵	4.61x10 ⁻⁴
Freshwater eutrophication	kg P eq	4.42x10 ⁻⁴	9.32x10 ⁻⁴	9.36x10 ⁻⁴	6.95x10 ⁻⁷	3.29x10 ⁻⁵
Marine eutrophication	kg N eq	2.00x10 ⁻²	8.24x10 ⁻⁴	9.35x10 ⁻⁴	1.73x10 ⁻⁶	3.28x10 ⁻⁵
Agricultural land occupation	m ²	5.15x10	2.86x10 ⁻¹	2.91x10 ⁻¹	1.33x10 ⁻⁴	3.17x10 ⁻³

The environmental results of our life cycle analysis study on ham production are comparable to those of previous related research. According to Carlsson–Kanyama [10], the energy requirement for pork in Sweden was 32 MJ. In general, important differences are observed between countries due to differences in the applied energy sources. These differences with data from Sweden can therefore be explained by the different energy sources used by the two countries. Additionally, this study considered all steps up to the point of sale, but the product has not been treated after being slaughtered. Compared to cooked ham, the difference is probably largely due to the extent of the contribution of ham production and storage on the distribution and product use stages. Therefore, in our study we considered more impacts. In addition, according to Reckmann et al. [72], the nonrenewable energy demand is 19.5 MJ.kg⁻¹ for slaughtered pork, with a contribution of 13% for the slaughtering stage. In this respect, the conventionally cooked ham had a very high energy consumption (87.7%), with a contribution of 10% from slaughtering. The breed from the previous study conducted in Sweden was not the same type of breed that is used in France because, according to the Agribalyse database, the nonrenewable energy consumption for a conventional pig raised in France is equal to 17.3 MJ.kg⁻¹ pork (live weight). These differences originate from the processed meat product due to the high raw material requirements (pieces of ham) and the steps required (cutting, cooking, and slicing) to produce a superior cooked ham. Despite the importance of limiting energy demand in sustainable food production [73], in the studies available on processed meat products, this impact category was not evaluated. Studies on the energy demand of meat products are

needed to identify and control or reduce the potential for preservation processes with a high potential environmental impact.

The carbon footprint of cooked ham (13.422 and 13.439 kg CO₂ eq.kg⁻¹) was similar to that obtained in other studies. In France, the carbon footprint of cooked ham was studied by the research firm BioIntelligence Service. Their superior cooked ham had a carbon footprint that varied from 7.71 to 8.55 CO₂ eq.kg⁻¹ (equivalent corresponding to the functional unit of this study) depending on the product (different numbers of slices, with or without the rind) [74]. The steps taken into account in the study by BioIntelligence Service were agriculture, manufacturing, distribution, transportation, and packaging. Between 63.1% and 75.9% of the potential for depletion of nonrenewable resources comes from the ham production phase and, more particularly, from the raw material production phase (in particular, pork). The consumption is mainly of electricity and gas on the farm (34.9%), as well as the consumption of fuel on the pig farm (26.4%), which contributes the most to the depletion of nonrenewable resources.

According to Carlsson–Kanyama [10], pork in Sweden has an impact of 6.1 kg CO₂ eq.kg⁻¹ meat (Roy et al. 2012). The CO₂ emission impacts are also dependent on the energy sources of each country. In this case, France could be associated with low CO₂ emissions because its electricity is predominantly nuclear. In terms of contribution, the main step was the production of raw material, followed by packaging, cooking, transportation, slaughtering, and storage. Distribution contributed to 3.3% of the impacts in this case. A rough estimate was given by our study for the distribution stage (4%). Another study on pork pie (2–3 kg CO₂ eq.kg⁻¹) produced in France showed that the production of raw materials also contributed 80% of the impact to the life cycle and that the processing stage contributed 10% to the cycle. The influence of transportation was negligible [13]. Our results were consistent with those of other studies: most of the impact of meat products comes from the agricultural production stage of the raw material. With regard to the depletion of abiotic resources, comparison with other studies on meat products was not possible because the depletion of nonrenewable mineral natural resources was not taken into account. However, the overall trend showed a decrease in the concentration of mineral ore [75]. According to the study by Reckmann et al. [72], slaughtered pork represents 57.1 g SO₂ eq.kg⁻¹. Slaughter yield and cooked ham production could be responsible for the difference in these emissions. The important contribution of raw material production to the eutrophication impact category was due to environmental emissions (nitrates in water and ammonia in the air) from intensive pig farming [76]. The emissions from a cooked ham were at least twice as high as those of a poultry product (19.9 to 29.9 g of PO₄³⁻.kg⁻¹ product, [77]) and as those of slaughtered pork (23.3 g PO₄³⁻.kg⁻¹ product, [72]).

3.2. The Potential Impact of Nitrosamines on Human Health

This study estimated that the exposure to exogenous nitrosamines (NDMA, NDEA, NPYR, and NPIP) by the daily consumption of cooked ham (16 g) was 0.15 ± 0.11 µg per day [78]. The variability in the product was associated with the quantification of the various nitrite compounds. Other studies on cooked ham were limited to the estimated NDMA concentration. For example, in our estimation, the exposure was lower than what was reported in work by Catsburg et al. [39]; the contribution of exogenous nitroso compounds was between 0 and 2.1 µg per day. In our study, this contribution ranged from 0.003 to 0.34 µg per day and corresponded only to the consumption of cooked ham. In addition to their use for preserving meat, nitrites are added to other foods to preserve them by limiting the proliferation of pathogenic microorganisms, in particular, *Clostridium botulinum*. Nitrates alone are used to prevent some cheeses from swelling during fermentation. They are also naturally present in some vegetables, with the highest concentrations occurring in leafy vegetables, such as spinach or lettuce. Moreover, these substances can enter the food chain as environmental contaminants in water due to their use in intensive agricultural practices, animal production and wastewater discharge. According to the European Food Safety Authority (EFSA) [79], based on realistic data, i.e., levels of

concentration actually observed in foods, the intake of nitrates in the form of a food additive is less than 5% of the global exposure to nitrates through food.

The development of gastrointestinal cancer is associated with exogenous exposure to nitroso compounds. The ingestion of exogenous nitrosamines in subjects with cancer was 0.0591 ± 0.0485 μg per day. However, this estimate corresponds to the NDMA compound in the diet [80]. Jakszyn et al. [81] also estimated dietary exposure to NDMA in a Spanish population at 0.114 μg per day. The foods that contributed most to this exposure are meat products (14%), beer (11%), and refined cheese (13%). In addition, a study on a European population showed that dietary exposure to NDMA was 0.26 ± 0.34 μg per day and 0.19 ± 0.31 μg per day for subjects with gastric cancer and for healthy subjects, respectively [82]. The exposure determined for the consumption of cooked ham for our study seemed high in comparison to these evaluations. However, the quantification of a single type of nitrosamine (NDMA) causes an underestimation of the risk of exogenous nitrosamines. In our case, the exposure to nitrosamines by the consumption of cooked ham decreased drastically if NDMA was the only nitrite compound taken into account: 0.065 ± 0.063 μg per day. In France, the exposure (NDMA) due to ham was estimated to be 0.0038 μg per day, with the presence of NDMA at 0.31 μg per kg ham and the annual ham consumption of 4.45 kg during the period of 1987–1992. The exposure to NDMA in the diet was determined to be 0.19 μg per day. Meat products contributed to 12.5% of NDMA exposure [83]. A preliminary study estimated a daily exposure of 0.25 μg (NDMA) per day per person in France [84]. In general, these studies only considered NDMA in assessing nitrosamine exposure.

The exposure to preformed nitrosamines was only considered for the estimation of the indicator. The severity of nitrosamines (2.2×10^{-6} DALY.kg⁻¹), considering the effect on an entire population and not limited to a sensitive population, was in line with a report from the International Agency for Research on Cancer (IARC) [31]. These experts recognized that there is strong evidence to support changing the recommendations for processed meat product consumption to achieve moderation or a reduction in consumption. Indeed, an increased risk of colorectal cancer is associated with higher consumption of meat products. The Global Fund for Cancer Research suggests that a reduction of 50 g meat product consumption per day could represent a 20% decrease in the number of colorectal cancer cases [85,86].

In regard to the human health indicators developed in this study, the potential impacts of food safety in the use phase were not negligible. The main aim of this study was to evaluate the potential contribution of nitrosamines to the damage of human health throughout the ham production life cycle. The impact on morbidity associated with contaminants from food processes is not currently known. However, the meat production industry is exploring alternatives to reduce or replace nitrites while preserving the microbiological and sensory quality of the products. An innovative combination of biopreservation and high-pressure processing has been explored to reduce nitrites in ham and contribute to reducing the total potential human health impact by almost 8% and almost 20% for the potential human health impact resulting from nitrosamine toxicity. Another option is the use of plant extracts with active molecules capable of inactivating microorganisms and/or preventing the negative effects of contaminants [87]. An additional option is to improve animal nutrition in such a way as to provide substances with a beneficial effect on health or even vitamins to react against the formation of these carcinogenic compounds [88,89]. Finally, a recent study has shown the influence of food processing conditions on the risk of cancer. A decrease in carcinogenesis in rats was linked to the anaerobic packaging of ham compared with unpackaged food and food exposure to air [90].

The innovative process of ham production combining high-pressure treatment and biopreservation could be a solution to not altering the concentration of residual nitrites in cooked ham [91–94]. Several high-pressure-treated meat products are marketed with the claim “nitrites/nitrates not added”. They contain natural preservatives, such as celery juice, that replace additives conventionally used in their preservation [95]. High-pressure

microbial inactivation can allow for the production of sausages without nitrite use while maintaining food safety [92,96]. This technology can also be used to improve the antimicrobial role of salt [97] or natural antimicrobials in ham [44,45]. Some potential impacts on human health could be avoided by specific innovative treatments involving these new technologies.

3.3. Sensitivity Analysis

Table 5 shows the impact results of the life cycle of cooked ham production in France in terms of damage-oriented impact categories from the ReCiPe method. All indicators are expressed in DALY and correspond to the chosen functional unit (1 kg of ham consumed). They describe the damage to human health attributable to each impact category.

Table 5. Indicators of the human health impact categories of the cooked ham life cycle for two scenarios (conventional and innovative ham).

Impact Category	Units	Conventional Ham	Innovative Ham
Photochemical oxidant formation	DALY	8.27×10^{-10}	8.29×10^{-10}
Ozone depletion	DALY	2.52×10^{-8}	2.52×10^{-8}
Ionizing radiation	DALY	3.77×10^{-8}	3.91×10^{-8}
Human toxicity	DALY	7.79×10^{-8}	7.82×10^{-8}
Nitrosamine toxicity	DALY	2.20×10^{-6}	4.54×10^{-7}
Particulate matter formation	DALY	4.98×10^{-6}	5.08×10^{-6}
Climate change	DALY	1.60×10^{-5}	1.60×10^{-5}

Climate change, particulate matter formation, and nitrosamine toxicity are major contributors to the human health impact category. In particular, nitrosamine toxicity presented a significant variation between the two scenarios, conventional ham versus high-pressure processed ham. The results for conventional ham were similar to those reported in the work of Weidema et al. [4]. The damage-oriented environmental impact of meat products in the European Union was mainly due to land use (32–49%), respiratory effects (inorganic (28–49%)), and climate change (15–23%). However, tackling the effects of nitrosamine on human toxicity is new and thus cannot be compared with the literature. Nitrosamines may become the third source of potential harm to human health after climate change and particulate matter formation, with an estimated contribution of up to 10% to the potential impacts. However, the integration of new impacts into LCAs implies a thorough knowledge of the mechanisms that limit the development of characterization factors [98]. For example, the International Agency for Research on Cancer has concluded that ingested nitrates or nitrites are likely human carcinogens when conditions induce the production of endogenous nitrosamines (IARC, 2010), which was not considered in this study. This is why efforts are needed to improve the understanding of these phenomena. Thus, the nitrosamine severity factor (11.5 DALY.cas⁻¹) used to quantify the damage to human health increased these uncertainties. The severity of colorectal cancer could be as high as 8.8 DALY, and that of stomach cancer could be as high as 13.6 DALY [99].

4. Conclusions

Food safety is a predominant attribute of a product in the implicit or explicit evaluation by the consumer, other stakeholders, and even the individuals involved themselves in the product life cycle. This study aimed to propose a multicriteria LCA-based approach, including environmental and human health indicators, to measure and compare the potential effects of a food product for different processing scenarios. A conventional LCA did not show a significant difference between two ham production scenarios, while the addition of human health indicators allowed them to be distinguished because for all impact indicators except nitrosamine toxicity, the variation between the two scenarios was less than 5%, which was considered negligible.

The impacts of life cycle steps on human health should be included in more food LCA studies. Indeed, these indicators are not negligible because this study showed that the product characteristics have a potential impact on human health that is comparable to other sources of environmental impact. Exposure to nitrosamines comes from various sectors of the environment. However, their presence in food is specific because the substances are preformed and because the food is a source of the precursors that allow for their formation in vivo. The complexity of these mechanisms makes it impossible to establish more reliable models to measure their total exposure and to define a more predictable degree of severity. Additional work aimed at better understanding this mechanism is necessary. The definition of indicators describing the potential impact of product life cycle steps on human health makes it possible to compare and evaluate several scenarios as part of a product-process innovation approach by highlighting the consequences of implementing such alternatives. A separate publication dedicated to the construction of several human health indicators linked to the addition or not of nitrites in ham will be proposed following this work. The potential impacts of a processed ham using new technologies could then be compared to those of a conventionally cooked ham. A comparative analysis of innovative processes as new life cycle steps would allow us to consider changes in product quality that may have consequences for human health and the environment.

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