Life Cycle Assessment of Environmental Sustainability and Nutritional Value of Animal Meat Substitutes

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The food industry is estimated to contribute to one-third of the global anthropogenic greenhouse gas emissions; thus, it is a major driver of climate change. Within food consumption patterns, animal-based foods are the main contributors to unfavorable environmental impacts. There is increasing evidence that suggests that animal products have a substantially larger climate impact than most plant-based foods, indicating that the shift from animal-based food diets to more plant-based food diets may help reduce environmental burdens. However, when replacing meat, it should be ensured that the nutritional requirements of consumers are met. The purpose of this study was to compare ground beef and plant-based meat production assessment to analyze the environmental sustainability and nutritional aspects using LCA. Using the NRF11.3 score to calculate and discuss the health score between ground beef meat (GBM) and plant-based meat (PBM). Our estimates suggest that the GBM contributes to global warming 8.01 times more than the PBM. Further, GBM is associated with 1.56 times more fossil fuel depletion, 2.87 times more land usage, and 1.81 times more water usage than PBM.

Key Words
Meat substitute, Nutritional value, Environmental impact

1. Introduction

Food production is estimated to cause one-third of global anthropogenic greenhouse gas (GHG) emissions and has therefore been identified as a major driver of climate change ⁵. Within food consumption patterns, animal-based foods are the main contributors to environmental impacts ⁶.

Among the different types of meat, beef has the largest, and chicken has the smallest, environmental impact in terms of climate change, land use, and fossil fuel depletion ⁷. An increasing number of studies have found that animal products have a substantially larger climate impact than most plant-based foods, indicating the potential for reducing environmental burdens by shifting from animal-based diets towards diets with more plant-based foods ⁸. It is important to reduce the environmental burden caused by food and change consumer behavior to promote dietary patterns with positive impacts on human health and the environment ⁹. The world’s human population is expected to grow to
approximately 10 billion by 2050. To meet the resulting increase in demand for food, agriculture in 2050 will need to produce almost 50% more food, animal feed, and biofuel in total weight than it did in 2012. Moreover, global food production is now able to feed more people than ever and the proportion of undernourished people in the world has fallen by 14.8% in 2000 to 10.8% in 2018. However, there remains substantial evidence of nutritional insufficiency.

Recently, people have become more interested in plant-based meat substitutes that are designed for cooking but made from only using plant protein to consist of a similar texture to fresh ground beef. However, when replacing meat, it should be ensured that the nutritional requirements of the consumers are met. Meat is an important source of high-quality proteins, iron, zinc, and vitamin B₁₂. Most of these important nutrients in meat can also be found in plant-based products but are present in different proportions, and often are in different forms. This study used the life cycle assessment (LCA) approach to quantify the environmental impacts while also considering nutritional values.

The purpose of this study was to compare ground beef meat (GBM) and plant-based meat (PBM) production to analyze their environmental sustainability as well as nutritional values using LCA. Using the NRF11.3 score, the health scores of GBM and PBM can be calculated and compared. The overall aim of this study was to emphasize the importance of dietary choices in environmental impact and nutritional value. By doing so, the analysis helps to build evidence to support the shift to a more sustainable diet.

GBM is derived from cattle that spend most of their lives grazing on grass in pastures but are "finished" for the last 120–200 days in a feedlot where they receive a scientifically formulated diet of grain, roughage, and nutrient supplements.

PBM is a meat substitute made from plants. It is specially designed and created to look, taste, and cook like conventional meat. Almost every PBM has different ingredients, but they are mostly made from extracted soybean protein or pea protein, spices, and other binding ingredients. While they are typically higher in sodium content, PBM is similar to real meat in terms of calories but has more fiber and less cholesterol.

2. Methodology

2.1 Scenarios: PBM and GBM

The PBM assessed in this study was made in Japan with ingredients imported from the United States, and GBM was also imported to Japan from the United States. The ingredients and the following system boundaries and geographical boundaries are shown in Table 1. About 60% of Japan’s beef is imported from overseas, principally from Australia and the United States. In this study, the United States was the target region for beef cattle production. In Japan, the self-sufficiency rate of soybeans is 7%, and the remaining 93% is imported from other countries. Among them, the United States is the largest importer of soybean imports from Japan, accounting for about 70% of soybean imports.

Legumes are reliable sources of protein, iron, and zinc. They can be used in the form of flour, protein concentrate, or protein isolate. In this study, the PBM consisted mainly of water and soy protein concentrate. Water was needed to ensure that the water content was between 55% and 65% of the PBM. Owing to its high protein content, which is comparable to meat, soybean is considered to be a suitable substitute for meat and is often the main ingredient for many meat replacers. In the beef replacers, iron, vitamin B₁₂, and zinc supplementations are necessary to meet the corresponding amounts that are present in meat. The specific compositions are shown in Table 2 and were obtained from Klara Van Mierlo and co-

| Table 2 Compositions of Plant-based meat |
|----------------------------------------|
| Composition    | Unit | Quantity |
|----------------|------|----------|
| Water          | kg   | 0.531    |
| Soy flour      | kg   | 0.074    |
| Soy protein concentrate | kg | 0.321 |
| Lupine protein isolate | kg | 0.072 |
| Iron additive  | mg   | 335      |
| B12 additive   | mg   | 3.92     |
| Zinc additive  | mg   | 706      |

| Table 1 System and geographical boundaries of the ingredients |
|-------------------------------------------------------------|
| Ingredients | System boundary | Geographical boundary |
|-------------|-----------------|-----------------------|
| Beef        | From cradle to factory gate | the United States     |
| Soy flour   | From cradle to factory gate | the United States     |
| Soy protein concentrate | From cradle to factory gate | the United States     |
| Lupine protein isolate | From cradle to factory gate | Global                |
In PBM, the system boundary in Fig. 1 includes the ingredient and end-product results. The ingredient results were calculated by summing the environmental impacts of the selected ingredients to the point of processing into the meat replacer. The end product results also comprise the environmental impact of the processing steps that convert the ingredients into a meat replacer.

The system boundary for GBM in the ground beef scenario is shown in Fig. 2, which is divided into three steps: crop farming, cattle production, and meat processing.

2.2 Nutrients

To assess the nutritional quality of the diets and obtain health scores, the nutrient-rich food index NRF11.3 was calculated according to Drewnowski and Fulgoni and co-workers. The Nutrient-Rich Foods (NRF) Index is a formal scoring system that ranks foods based on their nutrient content. When used in conjunction with environmental impact factors, it can help identify foods that are both nutritious and sustainable to the environment. The NRF11.3 was chosen as it has been shown to track diet quality more effectively and has achieved the best validation results when compared to other indices. It is based on nine nutrients to encourage (protein, fiber, vitamins A, C, E, and B12, minerals calcium, iron, magnesium, zinc, and potassium) and three nutrients to limit (saturated fat, added sugar, and sodium) for the human body. The NRF11.3 was calculated for each food product as follows:

\[ \text{NRF11.3} = \Sigma \text{NR} \cdot \Sigma \text{LIM} \]

where, \( \text{NR} \) represents the encouraged nutrients = 100 × (consumed amount of nutrient \( i \) per day divided by the recommended daily value of nutrient \( i \)) × the number of kcal consumed per food amount/serving size each day, in 100-kcal units. \( \text{LIM} \) represents the Nutrients that should be limited (saturated fat, added sugar, and Na) = 100 × (consumed amount of nutrient \( i \) per day divided by the maximum recommended daily value of nutrient \( i \)) × the number of kcal consumed per food amount/serving size each day, in 100-kcal units.

The recommended daily nutrient values were obtained from Drewnowski and the tolerable upper intake levels from the USDA.

2.3 Inventory data

The main nutritional data shown in Table 3 were retrieved from the online nutrient database of the United States Department of Agriculture and Klara Van Mierlo et al.

We elaborate on our findings based on a single functional unit. A functional unit was chosen to provide comparability between the two scenarios. In this study, 1 kg of GBM and PBM was chosen as the functional unit. The life cycle environmental impacts of the studied products were obtained from various sources, as shown in Table 4.

As Japan imports a large majority of its beef and soybean mainly from the US, we assumed that cattle and soybeans are grown in the US and imported to Japan. When data are used from different LCA studies, the system boundaries, functional unit, and allocation method should ideally be the same. All the consulted studies used a functional unit of 1 kg of product and applied economic

| Nutrients    | Unit | GBM (100 g) | PBM (100 g) |
|--------------|------|-------------|-------------|
| Energy       | KJ   | 735.00      | 637.92      |
| Calories     | kcal | 175.59      | 152.40      |
| Protein      | g    | 20.00       | 27.57       |
| Fiber        | g    | 0.00        | 5.09        |
| ALA (n-3)    | g    | 0.05        | 0.03        |
| LA (n-6)     | g    | 0.26        | 0.09        |
| Vitamin A    | μg   | 4.00        | 0.15        |
| Vitamin B12  | μg   | 2.21        | 2.11        |
| Vitamin C    | g    | 0.00        | 0.00        |
| Vitamin E    | mg   | 0.17        | 0.00        |
| Calcium      | mg   | 12.00       | 152.36      |
| Iron         | mg   | 2.24        | 6.86        |
| Zinc         | mg   | 4.79        | 6.57        |
| Saturated fat| g    | 3.93        | 0.03        |
| Added sugar  | g    | 0.00        | 0.00        |
| Sodium       | mg   | 66.00       | 290.38      |
Table 4 Inventory data of GBM and PBM

| Input                           | Unit | Quantity | Reference                     |
|---------------------------------|------|----------|-------------------------------|
| Total feed intake               | kg   | 23.2     | C. Alan Rotz et al., 2019     |
| Energy                          |      |          |                               |
| Fuel                            | L    | 0.36     | Senorpe Asem-Hiablie, 2018    |
| Natural gas                     | m³   | 0.03     | Senorpe Asem-Hiablie, 2018    |
| Electricity                     | kWh  | 0.41     | Senorpe Asem-Hiablie, 2018    |
| Land Use                        |      |          |                               |
| Drinking water                  | L    | 70.9     | C. Alan Rotz et al., 2019     |
| Water                           |      |          |                               |
| blue water                      | L    | 231      | Senorpe Asem-Hiablie, 2018    |
| output                          | kg*km| 8800     |                               |
| Transport, flight               |      |          |                               |
| Ammonia                         | g    | 86       | C. Alan Rotz et al., 2019     |
| Carbon dioxide                  | g    | 1102     | C. Alan Rotz et al., 2019     |
| Methane                         | g    | 454      | C. Alan Rotz et al., 2019     |
| Nitrous oxide                   | g    | 34.5     | C. Alan Rotz et al., 2019     |
| GBM                             | kg   | 1        |                               |

3. Results and Discussions

3.1 Nutrient results

The PBM exhibited a better NRF11.3 score (117.80) than the GBM (91.71) (Table 5, Fig. 3). PBM exhibited a significantly better nutritional value than GBM, particularly for protein, fiber, and calcium. As iron, B12, and zinc were added to PBM, the nutritional value of these three nutrients has almost the same or better nutritional value.

Table 5 Health scores of GBM (100 kcal) and PBM (100 kcal)

| Nutrients | GBM (100 kcal) | PBM (100 kcal) |
|-----------|----------------|----------------|
| Protein   | 22.78          | 36.18          |
| Fiber     | 0.00           | 13.36          |
| ALA (n-3) | 0.29           | 0.09           |
| LA (n-6)  | 8.32           | 3.34           |
| Vitamin A | 0.15           | 0.01           |
| Vitamin B12| 20.98         | 23.06          |
| Vitamin C | 0.00           | 0.00           |
| Vitamin E | 0.48           | 0.00           |
| Calcium   | 0.68           | 10.00          |
| Iron      | 7.09           | 25.01          |
| Zinc      | 18.19          | 28.72          |
| Saturated fat | 11.18       | 0.09           |
| Added sugar | 0.00          | 0.00           |
| Sodium    | 1.57           | 7.94           |
| NRF 11.3  | 91.71          | 147.80         |
than GBM. GBM does not contain fiber; PBM exhibited a higher score for fiber. \( \alpha \)-Linolenic acid (ALA) is an n-3, or omega-3, essential fatty acid. Linoleic acid (LA, 18:2 n-6) is an essential n-6 polyunsaturated fatty acid (PUFA) required for normal growth. Essential fatty acids of ALA (n-3) were not included in either nutrient composition, while LA (n-6) has a nutritional value of 8.32, exceeding the value of 3.34 for PBM. Vitamin A, vitamin C, and vitamin E do not exist for either nutritional value.

For the nutrients that should be limited, i.e., saturated fat, added sugar, and sodium, we found that GBM exhibited a high score of saturated fat, while PBM did not contain saturated fat. However, PBM has a higher sodium content, for a nutritional value of eight, compared with a score of two for GBM.

Meat is an important source of protein, iron, zinc, and vitamin \( B_12 \); and consequently we focus our discussion on these nutrients. As soybean was the main component of PBM, and lacks iron, zinc, and vitamin \( B_12 \), we included iron, zinc, and \( B_12 \) supplementation to the PBM composition to have the same nutrient contents of GBM.

Proteins account for approximately 18% of the total mass of the human body. Proteins are important raw materials for building and repairing the body. The development of the human body and the repair and renewal of damaged cells are inseparable from proteins. Ingested protein is digested in the body, hydrolyzed into amino acids, and absorbed, and then the protein needed by the body is synthesized. Essential amino acids refer to amino acids that the human body cannot synthesize or the rate of synthesis is too low to support the body’s needs. Essential amino acids must be obtained directly from food; otherwise, body’s nitrogen balance will not be maintained and this will affect health. To ensure sufficient protein quality, proteins are included at the level of individual essential amino acids: lysine, leucine, isoleucine, tryptophan, threonine, methionine+cystine, phenylalanine+tyrosine, and valine (Table 6).

![Fig. 3 Comparison of health scores for every nutrient](image)

Table 6 Nutritional value of essential amino acids in GBM and PBM

| Nutrients          | Unit | GBM(100g) | PBM(100g) |
|--------------------|------|-----------|-----------|
| Protein            | g    | 20.00     | 27.57     |
| Isoeucine          | g    | 0.89      | 1.26      |
| Leucine            | g    | 1.56      | 2.12      |
| Lysine             | g    | 1.66      | 1.97      |
| Methionine+cysteine| g    | 0.72      | 0.71      |
| Phenylalanine+tyrosine| g  | 1.40      | 2.36      |
| Threonine          | g    | 0.78      | 1.07      |
| Tryptophan         | g    | 0.10      | 0.35      |
| Valine             | g    | 0.98      | 1.30      |
In general, PBM contained higher protein quality than GBM. Soybeans are an abundant source of proteins and essential amino acids. The content of essential amino acids of soybeans, (isoleucine, leucine, phenylalanine + tyrosine, threonine, trypan, and valine), were significantly higher than GBM. The contents of essential amino acids, lysine and methionine + cystine were similar for GBM and PBM. In general, the protein content of PBM was not only higher than that of GBM, but the content of each essential amino acid was higher than, or equal to, that of GBM. Therefore, from the perspective of the nutritional value of proteins, PBM exceeded that of GBM.

Dietary fiber is a large group of carbohydrates that are part of the plant and are not digestible by the human body yet they have significant health benefits for the human body. The common feature of dietary fiber is that they have low energy value and cannot be decomposed and utilized by small intestinal enzymes. Moreover, the fermentation of dietary fibers by intestinal bacteria can produce short-chain fatty acids (SCFAs), which promote probiotics that exert a wide range of health benefits. In PBM, with soybeans as the main component, we found that its dietary fiber content was high, and no dietary fiber was present in GBM. This contributed significantly to the high nutritional score of PBM.

3.2 LCA results

Across all the scenarios, the burdens of PBM were significantly lower than those of GBM across climate change, land usage, water usage, and fossil fuel depletion. The results of the environmental factors of the two scenarios are shown in Table 7.

Our estimates (Fig. 4) indicate that the GBM contributes to global warming 8.01 times more than PBM. The GBM also needs 1.56 times more fossil fuels, 2.87 times more land, and 1.81 times more water than PBM.

In the GBM scenario, total feed consumed during the production of 1 kg Carcass weight of beef was approximately 23.2 kg dry matter with the majority (74%) consumed in the cow-calf phase. The total consumption was comprised of approximately 82% forage, 11% grain, and 7% by-product and waste product feed. Drinking water consumption varied more across regions because it was influenced by temperature. Similar to feed consumption, about 70% of the life cycle of drinking water was consumed.

| Environmental impacts          | Unit      | GBM  | PBM  |
|--------------------------------|-----------|------|------|
| Climate Change                 | kg CO₂ eq/kg | 26.2 | 3.27 |
| Land use                       | m²/kg     | 46.8 | 16.3 |
| Water use                      | L/kg      | 192  | 106.2|
| Fossil depletion               | MJ/kg     | 62.8 | 40.2 |

Fig. 4 Comparison of environmental impacts between GBM and PBM
during the cow-calf operations. Fossil energy use varied across regions and was primarily influenced by the size of the operations. Overall the regions, fuel usage averaged 0.36 L/kg CW. Natural gas is primarily used in large feedlots for grain processing. Important gaseous emissions in beef production include NH₃, CH₄, and N₂O emissions. NH₃ is emitted from urine and fecal excretions, which occur during all phases of cattle production. In beef cattle production, most CH₄ is produced by enteric fermentation. N₂O is primarily produced by the nitrification and denitrification processes in soil following urine deposition, fertilizer application, and stored in manure. Emissions of volatile organic compounds, including alcohols, also occur, primarily from silage production and manure storage. Nitrogen and phosphorus emissions to water are also considered in beef cattle production. Nitrogen is primarily lost in the form of NO₃⁻ leaching into groundwater, with much smaller amounts in surface runoff.

In this study, soybean emerged as the main ingredient for meat replacement because of its high nutritional protein content and low environmental impact values. PBM can be supplemented to enhance its nutritional value, which allows people to simultaneously consume essential amino acids, iron, vitamin B₁₂, and zinc. The compositions of PBM also included soy flour, soy protein concentrate, lupine protein isolate, and supplemental iron, B₁₂, and zinc.

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