Environmental impacts of cultured meat: alternative production scenarios

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ABSTRACT

Cultured meat is produced by culturing animal muscle tissue in a laboratory without growing the whole animals. Its development is currently in a research stage. An earlier study showed that cultured meat production could potentially have substantially lower greenhouse gas emissions, land use and water use compared to conventionally produced meat. The aim of this paper is to amend the previous study by considering alternative production scenarios. The impacts of replacing cyanobacteria based nutrient media with plant based media are assessed. This paper includes more specific modelling of a bioreactor suitable for cultured meat production. Further, this study estimates the water footprint of cultured meat based on a method that is compliant with life cycle assessment. The environmental impacts of cultured meat are compared with conventionally produced meat and with plant based protein sources. It is concluded that regardless of the high uncertainty ranges cultured meat has potential to substantially reduce greenhouse gas emissions and land use when compared to conventionally produced meat.

Keywords: in vitro meat, livestock, tissue engineering, carbon footprint, water footprint

1. Introduction

Livestock production contributes 15% of global greenhouse gas (GHG) emissions (Gerber et al. 2013), 33% of the global land use (FAO 2006), and 27% of the global water footprint (Mekonnen & Hoekstra 2011). The consumption of livestock products has been predicted to increase by 70% between 2010 and 2050 (Gerber et al. 2013). Conversion of forests to feed production is one of the main drivers of deforestation and degradation of wildlife habitats.

Tissue engineers have started developing in vitro technologies for producing edible meat. Their aim is to culture animal muscle tissue in a laboratory without growing the whole animals. Currently, cultured meat technology is in a research stage, and the first commercial products are predicted to be available within a decade. An earlier study showed that cultured meat production could potentially have substantially lower GHG emissions, land use and water use compared to conventionally produced meat (Tuomisto & Teixeira de Mattos 2011).

The aim of this paper is to amend the previous study by considering alternative production scenarios. The impacts of replacing cyanobacteria based nutrient media with plant based media are assessed. Cyanobacteria based growth media for tissue culturing is still under development, whereas plant based alternatives are currently available. The previous study had high uncertainty in the estimates of the energy requirements for the bioreactor used for culturing the cells. In this paper, the impacts of a different type of bioreactor, hollow fiber bioreactor, are assessed. Further, this study estimates the water footprint of cultured meat based on a method that is compliant with life cycle assessment (LCA) (Kounina et al. 2013). The environmental impacts of cultured meat are compared with conventionally produced meat and with plant based protein sources.

2. Methods

2.1. Goal of the study

The goal of this study is to estimate the energy use, GHG emissions, land use and water use for industrial scale production of cultured meat. LCA methodology based on ISO14040 and ISO14044 (2006) guidelines is used. The production is assumed to take place is Spain.

The water footprint method was based on recommendation by Kounina et al. (2013) to include only blue water footprint and use country specific water scarcity characterization factors. Both direct and indirect water use is included. Direct water use refers to the direct water inputs used in the process, whereas indirect use refers to the water needed for production of energy sources used in the process.

2.2. Scope definition

The functional unit (FU), towards which all the impacts are allocated, is 1000 kg of cultured meat with dry matter (DM) content of 30% and protein content of 19 % of mass. The cultured meat process described in this paper produces minced-beef type of product as the production technologies for steak type of products are under development. The muscle cells are grown in a bioreactor on a medium composed of a plant-based energy and nutrient source supplemented with the growth factors (proteins that stimulate cellular growth) and vitamins.

The system boundaries cover the major processes from input production up to the factory gate, including production of input materials and fuels, production of the feedstock, and cultivation of muscle cells. The production of growth factors and vitamins are not included in the study as the quantities needed are small (under 0.1% of the DM weight of the media), and therefore, the environmental impacts are assumed to be negligible.

Land use category includes the land requirement for cultivation of feedstock. The indirect land use associated with land use change and the production of energy inputs are not included in the study. The production of the animals that donate the initial cells for cultured meat is not included in the study due to the low number of cells needed.

The GHG emissions are assessed as global warming potential (GWP) by using the IPCC (2006) impact factors for 100-year timescale. The electricity and fuels used are converted to primary energy by using conversion factors that describe the amount of primary fuels required for extraction and supply of fuels. In this study it is assumed that electricity is used for sterilization and muscle cell cultivation. The emission of electricity production are based on an average European electricity generation portfolio.

2.3. Feedstock production

Three alternative feedstock sources of nutrients and energy for muscle cell production are compared: cyanobacteria, wheat and corn. Cyanobacteria are assumed to be cultivated in open artificial ponds. The details of cyanobacteria production are explained in Tuomisto and Teixiera de Mattos (2011). The data for wheat and corn production are based on Williams et al. (2006). After harvesting, the feedstock is sterilized and hydrolyzed in order to break down the cells. It was assumed that 2 kg of wheat or corn was needed for producing 1 kg of cultured meat. This is most likely an overestimate, but more accurate data was not available. The feedstock was assumed to be sterilized by using autoclaving before it was hydrolyzed. The data for blue water consumption or wheat and corn is taken from Mekonnen and Hoekstra (2011). The water scarcity characterization factors were based on data from Pfister et al. (2009), which give index of 0.715 for Spain.

2.4. Bioreactor

To achieve large scale production of cultured meat it is necessary to select the bioreactor configuration that provides a suitable physiological environment. The hollow fiber bioreactor replicates the capillary system found in most tissues. It has the added advantage of having the highest surface area to volume ratio of all bioreactors thereby reducing space and consumables costs.

Heating and pumping energy was balanced against heat energy generated by cell growth. The analysis included a best case and a worst case scenario. In the best case 95% cell viability with maximum theoretical cell yield of 2×10^8 cells/mL were assumed and 1×10^6 cells as the starting population. In the worst case 80% cell viability with half-maximum theoretical cell yield of 1×10^8 cells/mL and 2×10^4 cells as the starting population were assumed. The populations under all conditions were assumed to double every two days, and receive the required amount of nutrients and oxygen to achieve these cell densities.

Different sizes of reactors were assumed to be used during the 90 days production period, with increasing the size based on magnitude of volume required. The media was assumed to have the physical properties of water at 37 °C. The bioreactor material was 5mm thick stainless steel and lagging was 25mm thick glass wool. The hollow fibers membranes were made from polylactide. The fiber volume was negligible compared to the media volume and therefore ignored in the heat requirement calculations. The theoretical pumping requirements were calculated and a low efficiency of 0.5 was assumed; selection of the correct pump will improve this efficiency.

The nutrition media was initially heated from 4 °C to 37 °C for the bioreactor volume and for the media that is added during the culture period. The energy required to maintain a temperature of 37 °C is equal to the heat loss to the surroundings, and it was calculated based on the material properties, surface area and temperature differences. It was assumed that the surrounding temperature was 25 °C and that an electrical heating elements were used. The nutrition media was assumed to be changed every three days.

Taking the value of energy released per mole of electrons transferred to be 115kJ, the amount of energy released from the consumption of one mole of oxygen is 460 kJ. Therefore, the heat of reaction, assuming the cell culture is a fully aerobic system, is -460 kJ mol^{-1} of O_2 consumed (Doran 2013). The average oxygen uptake of cells in a culture can be taken as 5.455 x 10^{-12} mol $cell^{-1}$ day^{-1} (Goudar et al. 2011). This could then be multiplied by the heat of reaction to find the total amount of energy released in a day.

2.5. Comparison with other products

The results of cultured meat production were compared with livestock and vegetable products based on data from literature. The data about GHG emissions and land use of livestock products was from Nijdam et al. (2012), energy use from Williams et al. (2006) and water use from Mekonnen and Hoekstra (2010). When the results were reported in live weights or carcass weights, the conversion factors presented in Table 1 were used to attribute the impacts to edible meat. An economic allocation was used to allocate the impacts between the edible and non-edible parts of the animal. Non-edible part of the animal generally accounts for around 10% of the market value of the animal, and therefore, 90% of the impacts of producing the whole animal were allocated to the edible part.

The results of GHG emissions and land use of cultured meat production were also compared with livestock and vegetable products per unit of protein based on data from Nijdam et al. (2012).

Table 1. Conversion factors used to convert animal live weight or carcass weight to edible meat.

	Beef	**Pork**	**Sheep**	**Poultry**
Carcass weight of live weight	0.53	0.75	0.46	0.7
Edible meat of carcass weight	0.7	0.75	0.75	0.8

3. Results

The major energy input in the cultivation of cultured meat consists of heating energy required to heat the nutrition media and maintain the bioreactor temperature at 37 °C (Table 2).

Table 2. The results of energy requirements for hollow fiber bioreactor in the best and worst case scenarios.

	Best case GJ/FU	**Worst case GJ/FU**
Heating of reactors and media vessels*	8.12	14.60
Mixing media vessels	1.09E-04	1.95E-04
Aeration of media	0.07	0.13
Media pumping	1.93E-06	0.06
Total	**8.22**	**14.78**

*This is a balance of initial heating then maintaining the temperature of the media, and the energy released by the cells.

The results of the full LCA impacts of cultured meat are presented in Table 3. When comparing the feedstock source options, cyanobacteria had the lowest GHG emissions and land use, wheat had the lowest water footprint and corn the lowest primary energy requirement. Bioreactor energy use had the highest contribution to the energy input of cultured meat production. For GHG emissions, land use and water footprint, muscle cultivation and feedstock production had the highest contribution depending on the scenario.

When comparing the results of cultured meat with other livestock products, it was found that energy input requirement was at the same level with beef production, whereas GHG emissions and land use were lower than any of the livestock products (Figure 1). Water footprint was at the same level with poultry.

Table 3. Results of LCA impacts of cultured meat per functional unit (FU) of 1000 kg cultured meat.

	Primary energy GJ/FU	**GHG kg CO_2-eq/FU**	**Land use ha/FU**	**Indirect water use m^3/FU**	**Blue water for cultivation m^3/FU**	**Total water use m^3/FU**
Feedstock						
Cyanobacteria	8.1	611	0.046	6.1	249.5	255.7
Wheat	4.9	1608	0.260	3.7	68.1	71.8
Corn	3.9	1300	0.282	3.0	580.1	583.1
Biomass transportation	0.4	26		0.4		0.4
Sterilization	2.9	144		7.6		7.6
Materials for bioreactor	1.0	108		2.6		2.6
Muscle cell cultivation						
Best case	26.3	1380		57.1	193.1	250.1
Worst case	48.5	2493		57.1	193.1	250.1
Totals						
Cyanobacteria-best case	38.7	2268	0.046	73.8	442.6	516.4
Wheat-best case	35.5	3266	0.260	71.4	261.1	332.5
Corn-best case	34.5	2958	0.282	70.6	773.2	843.8
Cyanobacteria-worst case	60.9	3381	0.046	73.8	442.6	516.4
Wheat-worst case	57.7	4379	0.260	71.4	261.1	332.5
Corn-worst case	56.7	4071	0.282	70.6	773.2	843.8

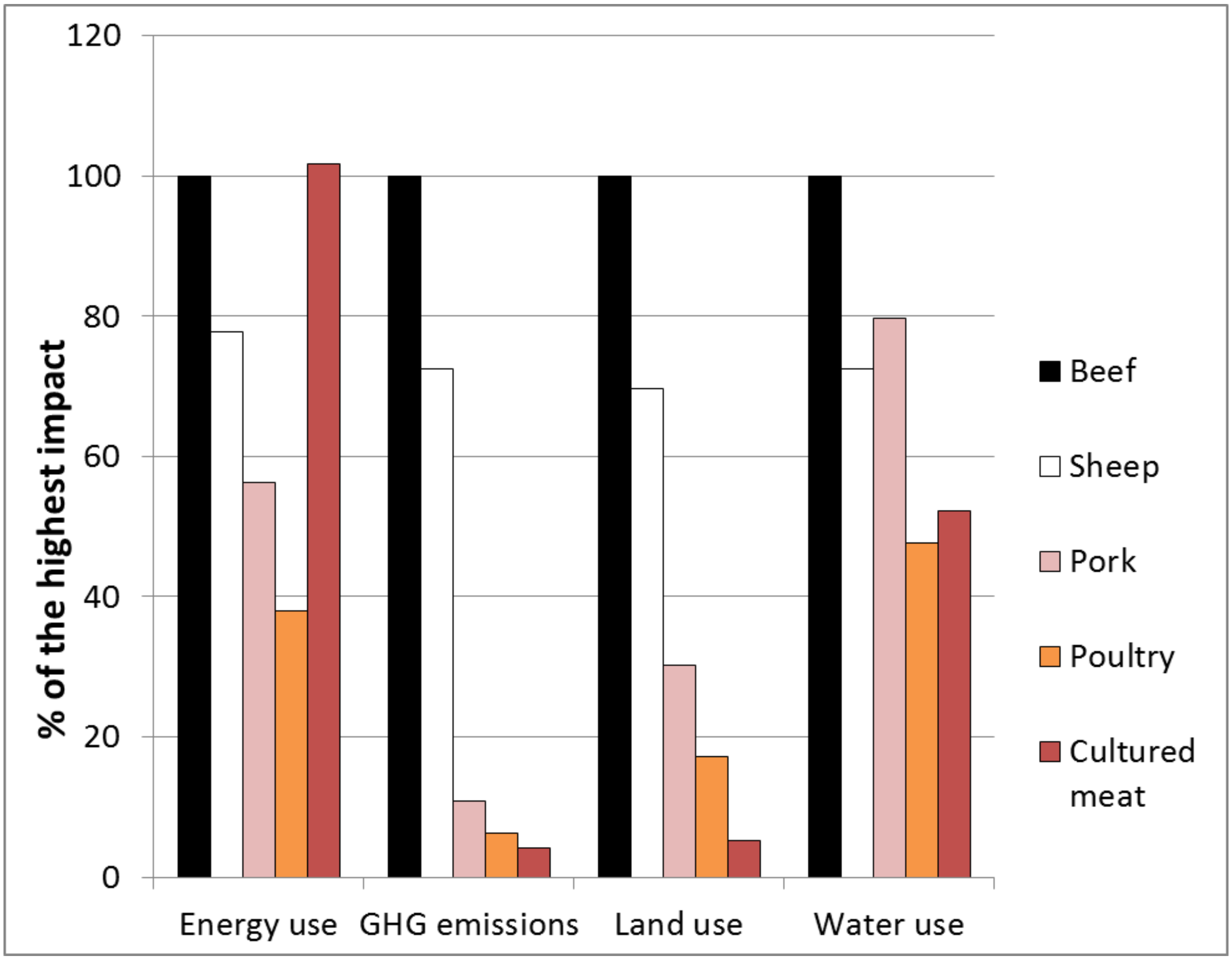

Figure 1. Comparison of environmental impacts of cultured meat with European livestock meat.

Figure 2 and 3 show the GHG emissions and land use of cultured meat compared with animal and plant based protein sources. The GHG emissions of cultured meat are at the same level with plant based protein and animal protein with the lowest carbon footprint. In terms of land use, cultured meat has the lowest land use requirements.

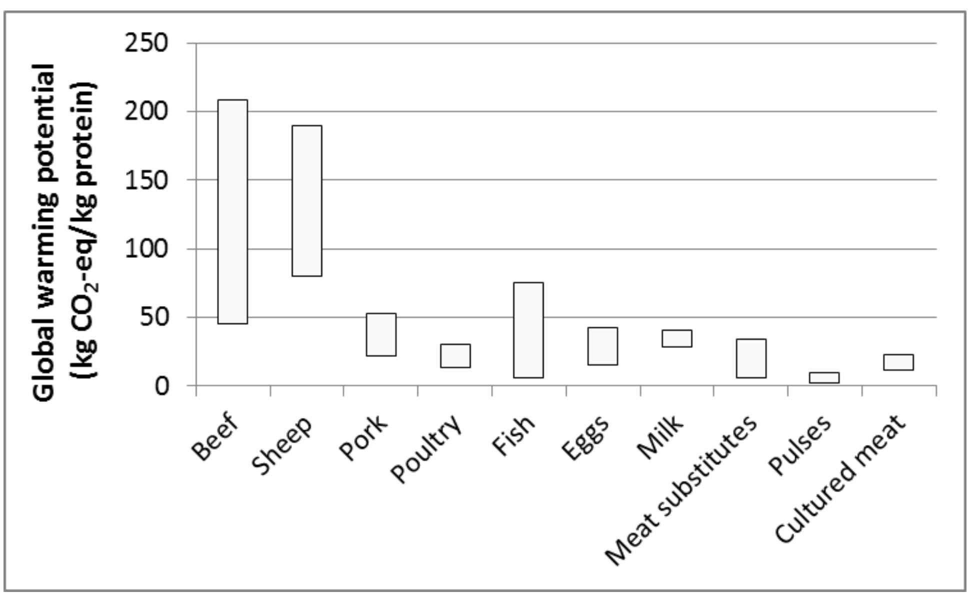

Figure 2. Comparison of GHG emissions of cultured meat with animal and plant based protein sources.

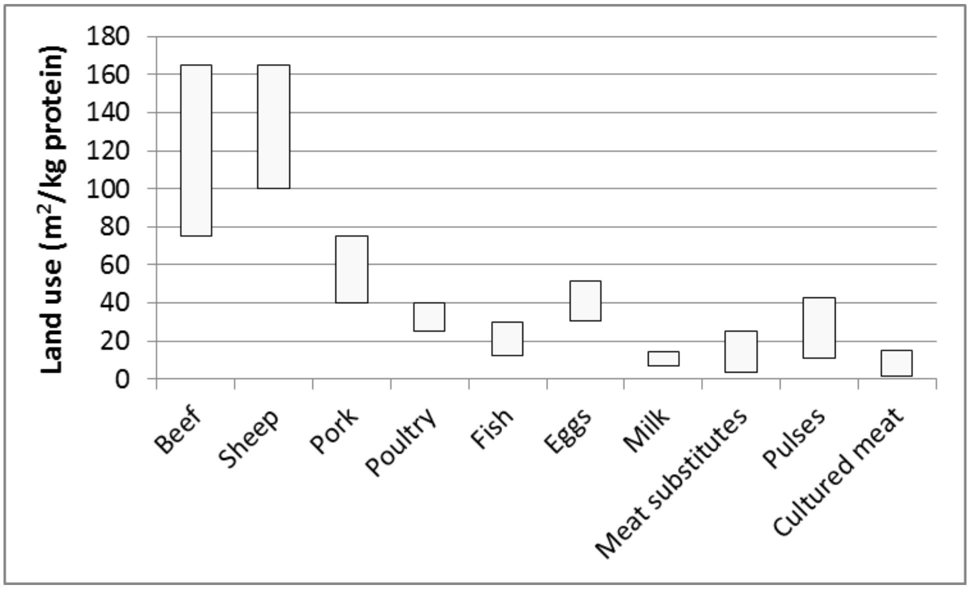

Figure 3. Comparison of land use of cultured meat with animal and plant based protein sources.

4. Discussion

As cultured meat production is still in research stage, the results presented in this paper have high uncertainty. The main uncertainty is related to the design of the bioreactor and composition of the nutrition media. Both have major impact on the environmental contribution of cultured meat production. The results of the hollow fiber bioreactor use are only preliminary hypothetical calculations. The energy requirement may be reduced by modifying the process, for example, by using heat exchangers. More research is required for developing suitable bioreactors for large scale cultured meat production.

Further research is also required for development of plant-based nutrition media for cell culturing. In this paper, only the impacts of producing the main ingredients of the nutrition media were included. More detailed assessment of impacts of producing the media should be performed once more information about a suitable plant-based media for cell culturing becomes available.

When comparing the current study with the results of Tuomisto and Teixeira de Mattos (2011), the main differences can be found in the energy input and water footprint results. The reason for higher energy input of cultured meat in this study is explained by more accurate modelling of the bioreactor and inclusion of bioreactor heating requirement.

The relative difference in the water footprint results is explained by updated methodology that includes only blue water footprint. Livestock production has high green water footprint, but relatively low blue water footprint.

5. Conclusion

We conclude that the uncertainties in the environmental impacts of cultured meat remain high. The alternative production scenarios compared in this paper help to better understand the sources of these uncertainty ranges. Regardless of the high uncertainty the results show that cultured meat could have substantially lower GHG emissions and land use when compared to conventionally produced meat. It is also important to take into account the consequential impacts of reduced land use requirements. If a large proportion of meat was produced by using cultured meat technology, land would be released from meat production for other uses. This land could potentially be used for provision of ecosystem services (e.g. for forests or natural conservation areas), which would increase the total environmental benefits of cultured meat production. More research on development of cultured meat technology is needed before more reliable estimates of the environmental impacts can be provided.

6. References

Doran PM (2013): Bioprocess Engineering Principles. Elsevier, Oxford

FAO 2006: Livestock's long shadow –environmental issues and options, Food and Agricultural Organization of the United Nations, Rome

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G 2013: Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities

Goudar CT, Piret JM, Konstantinov KB (2011): Estimating Cell Specific Oxygen Uptake and Carbon Dioxide Production Rates for Mammalian Cells in Perfusion Culture. Biotechnology Progress 27, 1347-1357

IPCC 2006: Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use.

ISO14044 (2006): Environmental management - Life cycle assessment - Requirements and quidelines. International Organization for Standardization

Kounina A, Margni M, Bayart J-B, Boulay A-M, Berger M, Bulle C, Frischknecht R, Koehler A, Milà i Canals L, Motoshita M, Núñez M, Peters G, Pfister S, Ridoutt B, Zelm R, Verones F, Humbert S (2013): Review of methods addressing freshwater use in life cycle inventory and impact assessment. The International Journal of Life Cycle Assessment 18, 707-721

Mekonnen MM, Hoekstra AY (2011): The green, blue and grey water footprint of crops and derivered crop products. Hydrology and Earth System Sciences 15, 1577-1600

Mekonnen MM, Hoekstra, A.Y. 2010: The green, blue and grey water footprint of farm animals and animal products, Delft, the Netherlands

Nijdam D, Rood T, Westhoek H (2012): The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37, 760-770

Pfister S, Koehler A, Hellweg S (2009): Assessing the Environmental Impacts of Freshwater Consumption in LCA. Environ. Sci. Technol. 43, 4098-4104

Tuomisto HL, Teixeira de Mattos MJ (2011): Environmental Impacts of Cultured Meat Production. Environ. Sci. Technol. 45, 6117-6123

Williams AG, Audsley E, Sandars DL 2006: Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities, Bedford

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