Life cycle assessment of cultured meat production

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ABSTRACT

Cultured meat is produced *in vitro* by using tissue engineering techniques. It is being developed as a potentially healthier and more efficient alternative to conventional meat. The goal of this study was to estimate energy use, land requirements, and greenhouse gas (GHG) emissions for large-scale cultured meat production. Life cycle assessment (LCA) research method was used for assessing the environmental impacts along the production chain. Cyanobacteria hydrolysate was assumed to be used as the nutrient and energy source for muscle cell growth. The results showed that cultured meat production involves approximately 35-60% lower energy use, 80-95% lower GHG emissions and 98% lower land use compared to conventionally produced meat products in Europe. Conventionally produced poultry had slightly lower energy use than cultured meat. It is concluded that the overall environmental impacts of cultured meat production are substantially lower than those of conventionally produced meat.

Keywords: *in vitro* meat, environmental impacts, energy use, greenhouse gas emissions, land use

1. Introduction

Meat production is one of the major contributors to global environmental degradation. Currently, livestock raised for meat uses 30% of global ice-free terrestrial land and produces 18 % of global greenhouse gas (GHG) emissions, which is more than the global transportation sector (FAO, 2006). Livestock production is also one of the main drivers of deforestation and degradation of wildlife habitats. Due to increasing population size and per capita meat consumption in the developing world, global meat consumption is expected to double between 1999 and 2050 (FAO, 2006). Such an increase will also double meat's impacts on the environment unless more efficient meat production methods are adopted.

One proposed method for reducing the negative environmental impacts of meat production is to grow only animal muscle tissue *in vitro*, instead of growing whole animals (Edelman *et al.*, 2005). This technology is called cultured meat (or *in vitro* meat) production, and it is currently in a research stage. The aim of this paper is to estimate the potential environmental impacts of large-scale cultured meat production and compare them with conventionally produced meat products.

2. Materials and methods

The goal of this study is to estimate the energy use, greenhouse gas emissions and land use of cultured meat production. Life Cycle Assessment (LCA) methodology based on ISO14044 guidelines is used (ISO, 2006). 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 19.1%.

The system boundaries cover the major processes from input production up to the factory gate (Figure 1), including production of input materials and fuels, production of the feedstock, and growth of muscle cells. It is assumed that cyanobacteria hydrolysate is used as the source of nutrients and energy for muscle cell production. Cyanobacteria are assumed to be cultivated in an open pond. The protein content of cyanobacteria species varies generally between 50-70% of DM (Richmond, 1988), and in this study a protein content of 64% of DM was assumed. After harvesting, the cyanobacteria biomass is sterilised and hydrolysed in order to break down the cells. The stem cells are taken from an animal embryo. The quantity of stem cells needed for producing 1000 kg cultured meat is relatively low, and therefore the impacts related to the production of the stem cells are not included in this study. Engineered *Escherichia coli* bacteria are used for the production of specific growth factors that induce the stem cells to differentiate into muscle cells. The muscle cells are grown on a medium composed of the cyanobacterial hydrolysate supplemented with the growth factors and vitamins in a bioreactor. The production of growth factors, vitamins and the animals used for source of the stem cells are not included in this study, due to their minor contribution to the results.

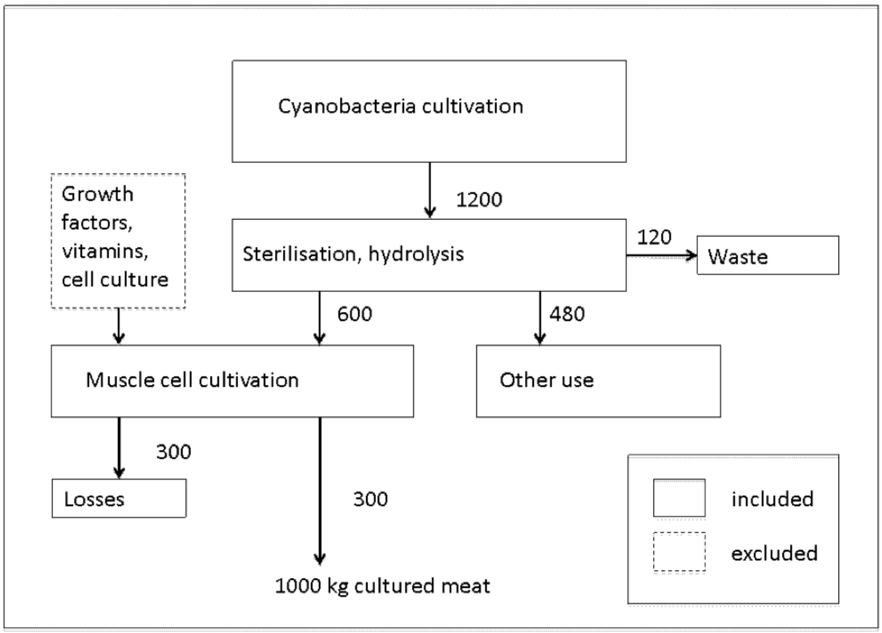

Figure 1: The system diagram of cultured meat production and the cyanobacteria biomass flows (kg DM)

The primary energy conversion factors and GHG emission factors for energy sources are based on the European Reference Life Cycle Database (ELCD, 2009) and Cherubini *et al*. (2009). In this study it is assumed that diesel is used in the cultivation of cyanobacteria operations and transportation of the biomass, and electricity for sterilisation and muscle cell cultivation.

It is assumed that cyanobacteria hydrosylate is used as an energy and nutrient source for the growth and proliferation of the muscle cells. Nitrogen-fixing cyanobacteria species are assumed to be used. Cyanobacteria biomass is assumed to be cultivated in an open pond (0.30 m deep) and harvested by using sedimentation and continuous vacuum belt filters. The energy requirements used for cultivation of cyanobacteria, harvesting, fertiliser production and construction and maintenance of the facility are based on the data from Chisti (2008).

Recorded annual production quantities of cyanobacteria vary globally between 7-110 tDM ha^{-1} (Richmond, 1988; Belay, 1997). In this paper cyanobacteria yield of 30 tDM ha^{-1} $year^{-1}$ and 25 g m^{-2} d^{-1} are assumed.

It is assumed that the cyanobacteria biomass is transported without drying for 50 km, assuming an energy need of 2.6 MJ t^{-1} km^{-1} (Liu and Ma, 2009).

Table 1 shows the specifications used for sterilisation and the cultivation processes. The volume of the culture is assumed to be 30 m^3, by assuming maximum muscle cell density of $1*10^{10}$ cells dm^{-3} and weight of a cell $1*10^{-12}$ kg.

It is assumed that the bioreactor is made from stainless steel. Production of 1 kg stainless steel requires 30.6 MJ primary energy and emits 3.38 kg CO_2-eq kg^{-1} (ELCD, 2009). The bioreactor is assumed to be used for 20 years.

Table 1: Specifications for sterilisation of cyanobacteria biomass and cultivation of muscle cells.

Sterilisation
Method: autoclaving
volume 1500 l, power 140 kW, temperature 220°C, time 20 min
Muscle cell cultivation
Method: cylinder stirred-tank bioreactor
volume 1000 l, height 1.72 m, diameter 0.86 m, weight 93 kg, 80% maximum filling capacity, cell density $1*10^{10}$ cells dm^{-3}, time per run 60 days, temperature 37°C, rotation 100 rpm, aeration 0.05 vvm, power input for agitation 25 W m^{-3} (Varley and Birch, 1999), power requirement for aeration was 16 W m^{-3} (Harding *et al*., 2007)

3. Results

Total energy use and GHG emissions of producing 1000 kg cultured meat are presented in Table 2. The energy use for producing cyanobacteria accounts for approximately 8% of total energy use and 15% of GHG emissions. The cultivation process of muscle cells has the greatest contribution to the results, accounting for 80% of total energy use and 74% of total GHG emissions. Sterilisation of the cyanobacteria biomass accounts for approximately 11% of total energy use and 9% of GHG emissions. Transportation of the cyanobacteria biomass to the cultured meat production facility has only a minor contribution (less than 2%) to both of the impacts.

The land requirements for producing feedstock for cultured meat production vary according to the location of the facility. Here it is estimated that the world average land requirement for cultivation of cyanobacteria is approximately 240 m^2 ha FU^{-1}. In the highest-yielding regions, the land requirement may be as low as 120 m^2 FU^{-1}, while in the lowest-yielding regions the land requirement may be as high as 480 m^2 FU^{-1}.

Table 2: Primary energy use and greenhouse gas (GHG) emissions of producing a Functional Unit (FU) of 1000 kg cultured meat

	Primary Energy GJ FU^{-1}	**GHG emissions** kg CO_2-eq FU^{-1}
CULTIVATION OF CYANOBACTERIA		
Construction and maintenance	0.68	66
Cultivation	1.49	145
Harvesting	0.05	5
TOTAL	2.22	217
BIOMASS TRANSPORTATION	0.37	26
STERILISATION	2.87	144
MUSCLE CELL CULTIVATION		
Steel production	0.98	108
Aeration	7.89	396
Rotation	12.32	618
TOTAL	21.19	1122
TOTAL	**26.64**	**1508**

4. Discussion

The results show that cultured meat production emits substantially less GHG emissions and requires only a fraction of land compared to conventional meat production in Europe (Table 3). Energy requirements of cultured meat production are lower compared to beef, sheep and pork, but higher compared to poultry production. As a comparison with cultivated Atlantic salmon (Pelletier and Tyedmers, 2007), cultured meat has approximately 36% lower energy input and 53% lower GHG emissions.

Table 3: Environmental impacts of producing 1000 kg of edible meat (calculated from original data)

Source	**Energy use** GJ	**GHG emissions** t CO_2-eq	**Land use** ha
Cultured meat (this study)	26.64	1.5	0.02
Beef			
Casey and Holden (2006)		55	
Kumm (2002)			1.35
Williams *et al*. (2006)	71.83	40.97	5.96
Elferink and Nonhebel (2007)			7.52
Lamb			
Williams *et al.* (2006)	50.71	38.2	3.03
Pork			
Kumm (2002)			1.57
Basset-Mens and van der Werf (2005)	47.59	6.88	1.63
Williams *et al*. (2006)	37.48	14.25	1.66
Elferink and Nonhebel (2007)			2.24
Dalgaard *et al.* (2007)		8.46	2.04
Poultry			
Williams *et al*. (2006)	23.3	8.90	1.24
Elferink and Nonhebel (2007)			1.46

The energy input calculations of cultured meat production in this study are based on many assumptions, and therefore, have high uncertainty. Energy consumption for cultured meat production may be higher if additional processing is required for improving the texture of meat. However, the efficiency of both cultivation of cyanobacteria and muscle cell cultivation can be improved by technology development. For example, closed bioreactors for cyanobacteria and microalgae production could improve the efficiency of biomass production (Ugwu *et al.*, 2008).

Table 3 shows that the energy input for cultured meat production is 63, 47 and 37 % lower compared to conventionally produced beef, sheep and pork, respectively, but requires 14 % more energy compared to conventionally produced poultry. However, energy input alone does not necessarily provide a sufficient indicator about the energy performance, if the opportunity costs of land use are not taken into account (Tuomisto *et al.*, 2009). Cultured meat production requires only about 2% of the land area that is used for producing the same mass of conventionally produced poultry meat. Therefore, more land could be used for bioenergy production and it can be argued that the overall energy efficiency of cultured meat would be more favourable.

As the majority of GHG emissions during the production of cultured meat are associated with the use of fuels and electricity, the emissions could be reduced by using renewable energy sources. In conventional meat production, the potential for reducing GHG emissions is more limited, because most of the emissions are due to methane from manure and ruminants' enteric fermentation, and nitrous oxide from soil. The replacement of conventionally produced meat by cultured meat could potentially contribute to the mitigation of GHG emissions, because instead of clearing more land for agriculture, large land areas could be reforested or used for other carbon sequestration purposes.

Cultured meat production could also have potential benefits for wildlife conservation for two main reasons: i) it reduces pressure for converting natural habitats to agricultural land, and ii) it provides an alternative way of producing meat from endangered and rare species that are currently over-hunted or – fished for food. Cultured meat production also has substantially lower nutrient losses to waterways compared to conventionally produced meat, since wastewaters from cyanobacteria production can be more efficiently controlled compared to run-offs from agricultural fields.

This study concentrated only on the production chain from input production up to the factory or farm gate, and therefore, does not provide the full comparison of the impacts during the whole life cycle of the products. However, it can be estimated that the relative impacts of cultured meat maybe even lower if the whole product life cycles were compared. The transportation requirements for cultured meat are likely to be lower, since whole animals are not transported and the production sites may locate closer to the consumers. Also refrigeration needs may be reduced, since cultured meat would potentially have less microbial contaminants compared to slaughtered meat. Further research is needed for estimating the total environmental impacts of cultured meat production during the whole life cycle from production to the consumer.

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