Techno-economic assessment and media cost modelling

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1. Overview / Summary

A techno-economic model was developed based on Cellular Agriculture Ltd.'s proprietary hollow fibre bioreactor centred bioprocess. A process model was formulated around 1 year's operation. Operating cost (OPEX) was estimated based on this process model (see variable cost estimation) and capital cost (CAPEX) estimated based on requisite buildings, equipment and installation cost estimates (see fixed cost estimation).

For each model scenario, a breakdown of OPEX and unitised CAPEX allowed for a cost of goods calculation on a per kg of cultured meat basis. No costs for conversion of the cultured biomass to final product were accounted for. Scenarios were catered for by adjusting the relevant parameters within the model to generate scenario-specific outputs.

Additionally, media costs were developed based on component cost data generated within the project. Briefly, prospective formulations were developed based on DMEM as a basal media formulation baseline. A formulation model was developed to allow for bottom-up formulation of amino acids and energy source (glucose), as well as requisite buffers, salts and vitamins etc. Amino acids, identified as a key cost and carbon driver, were built up from a combination of prospective valorised amino acid sources, and balanced using pure amino acids to give an approximate match to the DMEM baseline.

2. Introduction

The CM&F programme proposed a prospective economic study of cultured meat production to investigate the hypothesis that farm scale production of culture meat may be a viable endeavour for UK farmers to become part of, and diversify into, potential future farming opportunities, against the backdrop of the need for lower carbon initiatives. The approach taken was to assess two model scales with a view to assessing how cost-competitive smaller operations may be in comparison to larger industrial scale operations. Given many sources state the cost of cultured meat is driven in a large part by the cost of media, as assessment of differing types of media from current low value or waste stream has been assessed with a view to prospecting opportunities for agriculture by/co-product incorporation into future value chains.

3. Methodology

Process model

A hollow fibre bioreactor (in HFB) process model was developed representative of seed train, proliferation of bovine primary cells, then differentiation to final muscle tissue. All stages of culture assumed HFB technology. Performance parameters (cell growth and maturation rates, densities, media usage etc.) were based on Cellular Agriculture's 2023 process performance data, with size and number of bioreactor vessels scaled to meet the production target.

Mass and energy balances were performed on the core bioreactor stages, as well as ancillary processes comprising media and other process liquid make-up and sterilisation, media storage, biomass harvest and downstream processing, cleaning and sterilisation, water and wastewater handling, media component and water recovery and recycle, and final biomass product packaging and cold storage. The specifics of the process flow is not disclosed.

For the purposes of this study, around 70% of total water and useful media regeneration was assumed. This is a relatively favourable case given for decentralised 'farm scale' production of cultured meat, the infrastructure and equipment inventory for reprocessing media at small scale is likely to be complex and hence unfeasible from a technical and economic standpoint.

Fixed cost estimation

Fixed costs were estimated based broadly on AACE Class V cost estimates. An equipment schedule was produced covering all major process, utility and waste treatment units within the process flow diagram, and equipment duty estimated. Relevant capacity factors and existing equipment base costs (obtained by Cellular Agriculture from relevant suppliers) were applied to arrive at final equipment costs. Building and land footprint was estimated based on equipment installation, and building costs aligned to existing UK high care meat production facilities of speculatively similar hygiene specification. Overheads for design, installation e.g. piping, contractor fees and preliminaries, and project contingency/risk were applied. Overall CAPEX for plant installation was unitised to CAPEX/kg by division of the annual throughput over an assumed 20 year depreciation period.

Variable cost estimation

Media, supplements and growth factors

As mentioned previously, prospective media formulations were developed using DMEM as basal media baseline. Three valorised amino acid sources were selected based on their favourable amino acid balance. These were rapeseed waste meal (RWM), bovine blood plasma concentrate (BBP) and, horn and hoof meal (HHM). Additional criteria for their selection were that they were of general interest in the wider Cultured Meat and Farmers programme. For example, bovine blood plasma concentrate is of speculative interest not only as an amino acid source, but has additional benefits that could aid better media formulation i.e. it could also be viewed as a serum replacement.

To formulate prospective amino acid blends, a model calculator was used to factor in the highest possible inclusion level of the target source into an amino acid blend to closely match that present in the DMEM baseline. An error factor of 10% was assigned. This essentially meant that the combined concentrations errors of each amino acid summed together could not be more than 10% away from the DMEM baseline. The same approach was taken for glucose however given its single-component nature. Relevant quantities of vitamins and all required inorganic salts were factored in to derived a dry powder formulation which could be costed.

For costing purposes, an opportunity cost was assigned to each material (amino acid sources and glucose) to simulate processing effort required. Pure amino acids, pure glucose, vitamins and salts were costed based on prior market research performed on the programme. This work enabled calculation of comparative values for a range of ingredient grades (pharmaceutical, food and feed grade) giving a useful insight into potentially competing regulatory and cost drivers.

It should be noted that whilst prospective formulations have been developed, these do not currently hold any biological significance in terms of their respective performance. If formulations are of interest, it would be down to the concerned party to quantify and optimise performance at a later stage.

Media supplementation and growth factor costs were estimated based on a sub-optimal and optimal case scenario. For worst case, the pharmaceutical grade costs of the respective components was taken based on the costs found in the data mining phase.

For the optimal case, a cost of £0.4/kg biomass was applied. This value has been used based on discussions between Cellular Agriculture and a supplier developing a serum replacement and non-growth factor chemical cocktail media additive (‘cocktail’) which will be capable of cost-effectively mimicking the biochemical cues associated with serum and differentiation factors.

In terms of overall media consumption, a value of 140 L/kg of cultured meat was assigned in line with that assumed by Hubalek et al., 2022.

Other liquids, reagents and buffers

Quantities and costs of other process streams was factored into the variable costs based on bulk chemical/ingredient pricing.

Energy and utilities

Energy consumption was determined by the summing all of the equipment energy, heating energy and steam raising energy used for a given model scenario. Typical energy intensive processes that occur in the process flow studied are media heating, formulation and sterilisation processes, steam-in-place sterilisation, cleaning water heating and pressure filtration e.g. membrane processes for component and water recovery. Cleaning chemical cost estimates were based generally on typical clean-in-place solution concentration and cleaning agents. Water costs were estimated based on a major UK water operator, and waste water costs estimated based on effluent costs, again from a UK water operator accounting for an estimated wastewater composition. Oxygen required for dissolved oxygen equalisation of growth media was assumed as being generated on site using pressure swing adsorption (PSA) columns. Energy was estimated based on PSA output relating to the required O_2 consumption of cells.

Labour

Generally a highly automated operation was assumed. Operating labour was assumed in plant areas where manual tasks are likely to be required e.g. filter changeovers, pallet movements in e.g. cold and dry stores, as well as control room operators. Labour overheads were applied for maintenance and engineering labour costs, operations supervision, quality lab technicians and lab management.

Materials

Estimates based on supplier information/datasheets allowed for costs of materials estimation. For example, sterile filters were estimated based on the number of steam-in-place duty cycles allowable before replacement. Other filters were estimated based on general service lifetime data from various sources. Aspect such as these enabled estimation of the amount and technical mix of plastics likely to be required in a cultured meat operation, informing the lifecycle assessment.

Operating Overheads

Engineering and maintenance of equipment was estimated as a fraction of overall CAPEX. A plant overhead was applied as a factor of the total labour cost to account for indirect operating costs.

Generation of life-cycle impact assessment (LCIA) inputs

Based on mass and energy balance, materials assessment and utilities, LCA inputs were generated in alignment with the categories in (Tuomisto et al., 2022) In general, the process model outputs energy and media consumption in a relatively linear fashion, i.e. doubling capacity means doubling energy. Whilst this is somewhat of an oversimplification, the scope of the endeavour was to identify speculative production costs and the impact of using media components from waste or alternative sources. As such, LCA inputs for media were dealt with separately to the production model LCA inputs. Any efficiencies associated with scale were deemed out of scope. This aspect would be valuable, more in-depth exercise to initiate at a later stage.

Model scenarios

For techno-economic assessment, four layers of scenarios were used to derive overall production costs. These are described below.

Production targets

A decentralised and centralised model was proposed. This represent a decentralised farm scale model with the expectation of 150 T/year production. In contrast, a centralised model is presented in which the production target is 60 T/week. This represents a small but significant proportion of a leading UK meat packaging operation, envisioning a cultured meat factory feeding the existing facility.

Media formulation

As described above, DMEM baseline was applied i.e. a chemically defined basal media developed from food grade components. This was compared to prospective media containing RWM, BBP and HHM.

Media component grades and supplementation.

Food grade media components were the default of reporting costs, however feed and pharmaceutical grade media component costs were also used for contrast. Additionally, the default cost contributor used was for the cocktail.

4. Results and Discussion

Prospective basal media formulations and calculated costs

Using the formulation and cost model, costs for various grade of media inclusive of waste sources are shown in Table 1,

Table 2,

Table 3. In comparison, the cost of DMEM at equivalent grades was calculated to be £0.03/L, £0.05/L and £4.67/L kg for feed, food and pharmaceutical grades respectively. It should be noted that these are solely ingredient costs so cannot be compared to finished products. It does indicate that by both reducing of ingredients from pharmaceutical to feed grade, and adding in a proportion of upcycled valorised components, 250-fold cost reductions may be achievable. This is already the endeavour of a number of cultured meat media and 'full-stack' companies in the UK and globally.

Table 1 - Media costs for formulations based on rapeseed waste meal combined with pure ingredients at various grades.

Component group	**Source**	**Valorised components**	**Pure components**	**Cost per kg powder or per L (£/kg or L)**		
		Wt. % in final basal media	Wt. % in final basal media	Pharmaceutical grade	Food grade	Feed grade
Sugar	e.g. potato pulp	26.42%	0.00%	£0.13	£0.13	£0.13
Amino Acid	RWM	4.91%	4.49%	£68.96	£0.55	£0.52
Vitamin	n/a	n/a	0.18%	£5.24	£0.47	£0.33
Inorganic	n/a	n/a	64.00%	£32.18	£1.01	£0.47
Total per kg dry basal media powder				**£106.52**	**£2.16**	**£1.45**
Total per Litre wet basal media				**£1.81**	**£0.04**	**£0.02**

Table 2 - Media costs for formulations based on horn and hoof meal combined with pure ingredients at various grades.

Component group	**Source**	**Valorised components**	**Pure components**	**Cost per kg powder or per L (£/kg or L)**		
		Wt. % in final basal media	Wt. % in final basal media	Pharmaceutical grade	Food grade	Feed grade
Sugar	e.g. potato pulp	26.42%	0.00%	£0.13	£0.13	£0.13
Amino Acid	HHM	6.36%	3.04%	£46.66	£0.43	£0.41
Vitamin	n/a	n/a	0.18%	£5.24	£0.47	£0.33
Inorganic	n/a	n/a	64.00%	£32.18	£1.01	£0.47
Total per kg dry basal media powder				**£84.21**	**£2.04**	**£1.34**
Total per Litre wet basal media				**£1.43**	**£0.03**	**£0.02**

Table 3 - Media costs for formulations based on bovine blood plasma combined with pure ingredients at various grades.

Component group	**Source**	**Valorised components**	**Pure components**	**Cost per kg powder or per L (£/kg or L)**		
		Wt. % in final basal media	Wt. % in final basal media	Pharma	Food	Feed
Sugar	e.g. potato pulp	26.42%	0.00%	£0.13	£0.13	£0.13
Amino Acid	BBP	4.82%	4.58%	£70.26	£0.56	£0.53
Vitamin	n/a	n/a	0.18%	£5.24	£0.47	£0.33
Inorganic	n/a	n/a	64.00%	£32.18	£1.01	£0.47
Total per kg dry basal media powder				**£107.81**	**£2.17**	**£1.46**
Total per Litre wet basal media				**£1.83**	**£0.04**	**£0.02**

Techno-economic assessment model scenario outputs

Table 4 shows a comparison to highlight the unworkable cost of using growth factors at present pricing. The cost of formulating a bottom up basal medium formulation based on an exact match for DMEM is a viable strategy, delivering cost estimated of around £20/kg.

Table 4 - Comparison between basal media with supplementation 'cocktail' and chemically defined differentiation medium.

Media scenario.	CAPEX [£/kg]	OPEX [£/kg]	Production Cost [£/kg]
'Cocktail'	£6.92	£13.28	£20.20
Defined serum-free differentiation medium (with growth factors)	£6.92	£15,530.28	£15,537.20

Both media scenarios are for food grade DMEM basal media baseline, farm scale production

Table 5 shows production costs for a kilo of finished cultured biomass. Of clear distinction of the capital cost proposition of the overall cost in a small scale facility – more than double a large scale centralised facility. Additionally, OPEX is around 20% higher for a scall scale facility. This in reality could be greater given the model does not account for delivery of materials, which given the smaller scale, will be proportionally greater too. Nevertheless, the final cost of good per kilo across all scenarios is relatively favourable, and this would further be improved by a higher water and media component recycling rates (reducing media cost), energy reduction, ongoing improvements in the cost of production equipment.

Table 5 - Comparison of cost of production between a farm scale centralised-type facility (150T/y) and an industrial centralised facility (60T/week)

Plant format	Media scenario.	CAPEX [£/kg]	OPEX [£/kg]	Production Cost [£/kg]
Farm-scale decentralised facility	DMEM	£6.92	£13.28	£20.19
	RWM		£13.72	£20.64
	HHM		£13.28	£20.19
	BBP		£13.72	£20.64
Industrial centralised facility	DMEM	£3.58	£11.09	£14.68
	RWM		£11.53	£15.12
	HHM		£11.09	£14.68
	BBP		£11.53	£15.12

All media scenarios are for food grade basal media components inclusive of the 'cocktail'.

Life-cycle impact assessment inputs and outputs

The production model was used to quantify the values summarised in Table 6. Oxygen consumption was estimated as previously discussed. Estimates for plastic usage were developed from quantities of respective components contained in commercial filtration and membrane elements. Water was categorised as media or process water, energy was divided between the facility and bioprocess energy, the energy requirement for water sterilisation, and energy required for media and waste re-processing.

Table 6 – LCIA production inputs generated from production model

Component	Source	Unit (per kg cultured meat)	Quantity
Oxygen	PSA	kg/kg	0.232
Polystyrene	Hollow fibres	kg/kg	1.29E-02
Polyethersulfone	Filters/membrane	kg/kg	4.71E-04
Polypropylene	Filters/membrane	kg/kg	4.71E-04
Polytetrafluorothene	Filters/membrane	kg/kg	5.15E-04
Water (media and process)	Mains water	L/kg	88.890
Wastewater	Process	L/kg	43.921
Water Treatment and Cleaning Energy	Mixed energy	kWh/kg	0.164
Water Sterilisation Energy	Mixed energy	kWh/kg	0.136
Bioprocessing and Facility Energy	Mixed energy	kWh/kg	3.989
Total Energy	**Mixed energy**	**kWh/kg**	**4.289**

For media and chemical inputs, see Appendix Table 7 *and* Table 8*.* For outputs*,* Tuomisto et al., 2022's values for lactate and ammonia were used. Waste water quantity is shown in Table 6.

All data generated was fed into a the LCIA discussed next[IA1].

5. Conclusions

A combined media formulation cost model and production model was developed to understand the costs and contribute data towards an LCIA. The results indicate that utilisation of low-grade feedstocks for media preparation are economically favourable. It also validates that the reduction of quality grades of key components (particularly amino acids) is a key aspect to reducing media costs. The model also looked at how process economics are influenced by plant scale, with main emphasis being on the cost of the installation. This revealed that small scale operations are likely to incur around 30% higher costs of goods than larger scale facilities, owed to the less favourable investment in the plant. There are also penalties around energy use, labour and hence various other production overheads.

It can therefore be recommended that emphasis on capital cost reduction in cultured meat is a likely to be a key driver in realisation of small scale, farm level production. This is already a major focus area for cultured meat companies working on scale technologies where incumbent engineering standard and qualities more closely resemble pharmaceutical grade equipment than food production equipment. Striking the balance between robust and safe food production whilst reducing or removing the level of quality validation required of pharmaceutical grade equipment is one major factor that will be required, to promote competitiveness of decentralised operations.

6. Appendix

Table 7 - LCIA media inputs. Values in italics are sourced from Tuomisto et al., 2022

Category	Parameters/ proxy	Constituents	Unit	Baseline (DMEM[1])	RWM	HHM	BBP
DMEM	Pure Amino Acids	L-Arginine	kg/kg	2.51E-02	4.00E-03	0.00E+00	0.00E+00
		L-Cysteine	kg/kg	1.87E-02	8.72E-03	8.72E-03	8.72E-03
		L-Glutamine	kg/kg	1.74E-01	5.88E-02	5.08E-02	6.49E-02
		Glycine	kg/kg	8.96E-03	0.00E+00	0.00E+00	2.07E-04
		L-Histidine.HCl.H20	kg/kg	1.25E-02	2.19E-03	3.61E-03	9.53E-04
		L-Isoleucine	kg/kg	3.14E-02	9.30E-03	6.98E-03	1.07E-02
		L-Leusine	kg/kg	3.14E-02	5.57E-03	0.00E+00	3.68E-03
		L-Lysine.HCl	kg/kg	4.36E-02	1.32E-02	1.14E-02	1.16E-02
		L-Methionine	kg/kg	8.96E-03	1.50E-03	7.38E-05	3.17E-03
		L-Phenylalanine	kg/kg	1.97E-02	4.07E-03	2.85E-03	3.15E-03
		Proline	kg/kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		L-Serine	kg/kg	1.25E-02	2.95E-05	0.00E+00	0.00E+00
		L-Threonine	kg/kg	2.84E-02	7.52E-03	4.28E-03	5.50E-03
		L-Trytophan	kg/kg	4.78E-03	5.91E-04	2.23E-03	8.46E-04
		L-Tyrosine.2Na.2H20	kg/kg	3.10E-02	1.07E-02	5.88E-03	8.86E-03
		L-Valine	kg/kg	2.81E-02	6.30E-03	2.46E-03	5.21E-03
	Vitamins	Choline Chloride	kg/kg	7.03E-05	7.03E-05	7.03E-05	7.03E-05
		Folic Acid	kg/kg	7.03E-05	7.03E-05	7.03E-05	7.03E-05
		myo-Inositol	kg/kg	1.27E-04	1.27E-04	1.27E-04	1.27E-04
		Niacinamide	kg/kg	7.03E-05	7.03E-05	7.03E-05	7.03E-05
		D-Pantothenic Acid.1/2Ca	kg/kg	7.03E-05	7.03E-05	7.03E-05	7.03E-05
		Pyridoxine.HCl	kg/kg	7.10E-05	7.10E-05	7.10E-05	7.10E-05
		Riboflavin	kg/kg	7.03E-06	7.03E-06	7.03E-06	7.03E-06
		Thiamine.HCl	kg/kg	7.03E-05	7.03E-05	7.03E-05	7.03E-05

	Sugars, buffers and other	Glucose	kg/kg	1.35E+00	1.35E+00	1.35E+00	1.35E+00
		Hypoxanthine Na	*kg/kg*	*1.02E-03*	*1.02E-03*	*1.02E-03*	*1.02E-03*
		Linoleic Acid	*kg/kg*	*1.79E-05*	*1.79E-05*	*1.79E-05*	*1.79E-05*
		Lipoic Acid	*kg/kg*	*4.47E-05*	*4.47E-05*	*4.47E-05*	*4.47E-05*
		Putrescine 2HCL	*kg/kg*	*3.45E-05*	*3.45E-05*	*3.45E-05*	*3.45E-05*
		Sodium Pyruvate	*kg/kg*	*2.34E-02*	*2.34E-02*	*2.34E-02*	*2.34E-02*
		Thymidine	*kg/kg*	*1.55E-04*	*1.55E-04*	*1.55E-04*	*1.55E-04*
	Inorganic Salts	CaCl2	kg/kg	3.52E-03	3.52E-03	3.52E-03	3.52E-03
		Fe(NO3).9H20	kg/kg	1.76E-06	1.76E-06	1.76E-06	1.76E-06
		MgSO4	kg/kg	1.72E-03	1.72E-03	1.72E-03	1.72E-03
		KCl	kg/kg	7.03E-03	7.03E-03	7.03E-03	7.03E-03
		NaHCO3	kg/kg	6.51E-02	6.51E-02	6.51E-02	6.51E-02
		NaCl	kg/kg	1.13E-01	1.13E-01	1.13E-01	1.13E-01
		NaH2PO4	kg/kg	1.92E-03	1.92E-03	1.92E-03	1.92E-03
		Cupric sulfate	*kg/kg*	*5.54E-07*	*5.54E-07*	*5.54E-07*	*5.54E-07*
		Ferric sulfate	*kg/kg*	*5.54E-07*	*5.54E-07*	*5.54E-07*	*5.54E-07*
		Magnesium Chloride	*kg/kg*	*5.54E-07*	*5.54E-07*	*5.54E-07*	*5.54E-07*
		Sodium phosphate dibasic anhydrous	*kg/kg*	*5.54E-07*	*5.54E-07*	*5.54E-07*	*5.54E-07*
		Zinc sulfate	*kg/kg*	*5.54E-07*	*5.54E-07*	*5.54E-07*	*5.54E-07*
	Trace elements	Cu	kg/kg	1.00E-04	1.00E-04	1.00E-04	1.00E-04
		Na Selenite	kg/kg	3.70E-04	3.70E-04	3.70E-04	3.70E-04
		Zn	kg/kg	3.00E-02	3.00E-02	3.00E-02	3.00E-02
	Supplements - Essential8 less F12/DMEM	L-Ascorbic Acid 2-phosphate	kg/kg	1.92E-02	1.92E-02	1.92E-02	1.92E-02
		NaHCO3	kg/kg	1.63E-01	1.63E-01	1.63E-01	1.63E-01
		Sodium Selenite	kg/kg	4.20E-06	4.20E-06	4.20E-06	4.20E-06
		Insulin	kg/kg	5.82E-03	5.82E-03	5.82E-03	5.82E-03
		Transferrin	kg/kg	3.21E-03	3.21E-03	3.21E-03	3.21E-03
		FGF-2	kg/kg	3.00E-05	3.00E-05	3.00E-05	3.00E-05
		TGF-Beta	kg/kg	6.00E-07	6.00E-07	6.00E-07	6.00E-07
Valourised Source	Refined Amino Acids	RWM	kg/kg	-	1.17E-01	-	-
		HHM	kg/kg	-	-	1.51E-01	-
		BBP	kg/kg	-	-	-	1.13E-01

Table 8 - Non-media chemical inputs for LCIA

Category	Parameters/ proxy	Constituents	Unit	Baseline (DMEM[1])	RWM	HHM	BBP
Cleaning	**n/a**	**Sodium Hydroxide**	**Kg/kg**	5.89e-2	5.89e-2	5.89e-2	5.89e-2

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