

Empirical economic analysis shows cost-effective continuous manufacturing of cultivated chicken using animal-free medium

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Supplementary Information

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Supplementary Table S1: Equipment list and ISBL direct costs for bulk cell mass production

	ATF			TFF			Large-Scale Perfusion		
Equipment	Quantity/Capacity	Unit Cost	Cost	Quantity/Capacity	Unit Cost	Cost	Quantity/Capacity	Unit Cost	Cost
<i>ISBL: Bioreactors</i>									
Production bioreactor	25 x 2 m ³	\$800,000	\$20,000,000	10 x 5 m ³	\$1,000,000	\$10,000,000	2 x 25 m ³	\$2,200,000	\$4,400,000
Seed bioreactor	1 x 0.5 m ³	\$600,000	\$600,000	1 x 0.5 m ³	\$600,000	\$600,000	1 x 2 m ³ , 1 x 0.25 m ³	\$1,100,000	\$1,100,000
Centrifuge	1 x 6 gpm	\$180,000	\$180,000	1 x 6 gpm	\$180,000	\$180,000	1 x 6 gpm	\$180,000	\$180,000
Downstream extrusion	1 x 200 kg/h	\$1,000,000	\$1,000,000	1 x 200 kg/h	\$1,000,000	\$1,000,000	1 x 200 kg/h	\$1,000,000	\$1,000,000
<i>ISBL: Other</i>									
Cell retention	50 x ATF 10	\$350,000	\$17,500,000	10 x TFF	\$175,000	\$1,750,000	2 x Large-Scale PD	\$1,210,000	\$2,420,000
Sterilizers, Auxiliary Tanks, Filtration	Combined	\$800,000	\$800,000	Combined	\$800,000	\$800,000	Combined	\$810,000	\$810,000
Missing capital	10%		\$4,008,000	10%		\$1,433,000	10%		\$991,000
Installation	0.3 x PEC ^a		\$5,490,000	0.3 x PEC ^a		\$765,000	0.3 x PEC ^a		\$969,000
ISBL: Total Direct Cost			\$49,578,000			\$16,528,000			\$11,870,000

^aOnly applied to "*ISBL: Other*"

Supplementary Table S2: Equipment list and OSBL direct costs for bulk cell mass production

	ATF			TFF			Large-Scale Perfusion		
Equipment	Quantity/Capacity		Cost	Quantity/Capacity		Cost	Quantity/Capacity		Cost
<i>OSBL</i>									
Vacuum PSA	15 kTA		\$1,990,750	15 kTA		\$1,990,750	15 kTA		\$1,990,750
O2 compressor	1,600 ACMH		\$68,750	1,600 ACMH		\$68,750	1,600 ACMH		\$68,750
NG boiler	1,400 kg/h		\$35,500	1,400 kg/h		\$35,500	1,400 kg/h		\$35,500
Steam generator	2 x 1500 kcal/h		\$140,000	2 x 1500 kcal/h		\$140,000	2 x 1500 kcal/h		\$140,000
Chiller	400 kW		\$111,250	400 kW		\$111,250	400 kW		\$111,250
Cooling tower	12 L/s		\$7,500	12 L/s		\$7,500	12 L/s		\$7,500
Missing capital	10%		\$235,375	10%		\$235,375	10%		\$235,375
Installation	0.3 x PEC		\$776,738	0.3 x PEC		\$776,738	0.3 x PEC		\$776,738
OSBL: Total Direct Cost			\$3,365,863			\$3,365,863			\$3,365,863

Supplementary Table S3: Building costs for 50KL facility

	ATF			TFF			Large-Scale Perfusion		
Building	\$/m ²	Area (m ²)	Cost	\$/m ²	Area (m ²)	Cost	\$/m ²	Area (m ²)	Cost
Production floor (CNC)	\$3,759	3,016	\$11,337,857	\$3,759	3,016	\$11,337,857	\$3,759	1,200	\$4,511,083
Cell lab (CNC)	\$3,759	30	\$112,777	\$3,759	30	\$112,777	\$3,759	30	\$112,777
QC lab (CNC)	\$3,759	15	\$56,389	\$3,759	15	\$56,389	\$3,759	15	\$56,389
Office	\$1,657	100	\$165,700	\$1,657	100	\$165,700	\$1,657	100	\$165,700
Compressor building	\$1,291	13	\$16,783	\$1,291	13	\$16,783	\$1,291	13	\$16,783
Shop	\$1,251	754	\$943,254	\$1,251	754	\$943,254	\$1,251	300	\$375,300
Warehouse	\$1,132	754	\$853,528	\$1,132	754	\$853,528	\$1,132	754	\$853,528
Cold storage	\$3,759	70	\$263,147	\$3,759	70	\$263,147	\$3,759	70	\$263,147
Slab	\$135	4,752	\$641,520	\$135	4,752	\$641,520	\$135	2,482	\$335,070
Buildings total			\$14,390,954			\$14,390,954			\$6,689,777

Supplementary Table S4: Indirect costs and total capital investment (TCI) summary

	ATF			TFF			Large-Scale Perfusion		
ISBL direct cost			\$49,578,000			\$16,528,000			\$11,870,000
OSBL direct cost			\$3,365,863			\$3,365,863			\$3,365,863
Buildings			\$14,390,954			\$14,390,954			\$6,689,777
Total Direct Cost (TDC)			\$67,334,816			\$34,284,816			\$21,925,639
Engineering & Construction	0.6 x TDC		\$40,400,890	0.6 x TDC		\$20,570,890	0.6 x TDC		\$13,155,383
Total Plant Cost (TPC)			\$107,735,706			\$54,855,706			\$35,081,023
Fees & Contingency	0.15 x TPC		\$16,160,356	0.15 x TPC		\$8,228,356	0.15 x TPC		\$5,262,153
Total Capital Investment (TCI)			\$123,896,062			\$63,084,062			\$40,343,176
Annual Capital charge	14.6% TCI/y		\$18,088,825.02	14.6% TCI/y		\$9,210,273.02	14.6% TCI/y		\$5,890,103.70
Overall Lang factor estimate (TCI/PEC)			5.7			5.4			7.1

Supplementary Table S5: Variable operating cost culture medium

	Serum-Free Medium (SFM)					Animal Component-Free Medium (ACF)				
Nutrients	Unit	Per year	\$/y	\$/kg	\$/kg Protein	Unit	Per year	\$/y	\$/kg	\$/kg Protein
Sugars & Polysaccharides	kg	135,997	\$7,221,077	\$7	\$675	kg	151,643	\$1,203,513	\$1.12	\$112
Amino Acids	kg	93,633	\$7,221,077	\$7	\$675	kg	86,653	\$2,647,728	\$2.47	\$247
Fatty Acids & Lipids	kg	722	\$2,407,026	\$2	\$225	kg	722	\$1,684,918	\$1.57	\$157
Vitamins & Minerals	kg	247,924	\$19,256,205	\$18	\$1,800	kg	161,271	\$3,129,133	\$2.92	\$292
Growth Factors	kg	48	\$7,221,077	\$7	\$675	kg	2	\$180,527	\$0.17	\$17
Albumin	kg	60,176	\$24,070,256	\$22	\$2,249	kg	-	-	-	-
Others	kg	6,499	\$13,479,343	\$13	\$1,260	kg	4,814	\$6,258,267	\$5.85	\$585
Total nutrients ^a		544,999	\$80,876,060	\$75.58	\$7,557.97		405,105	\$15,104,086	\$14.11	\$1,411.50

Supplementary Table S6: Variable operating cost consumables

	ATF					TFF					Large-Scale Perfusion				
Consumables	Unit	Per year	Unit Cost	\$/y	\$/kg	Unit	Per year	Unit Cost	\$/y	\$/kg	Unit	Per year	Unit Cost	\$/y	\$/kg
Filter membrane	ea	600	\$16,300	\$9,780,000	\$9.14	ea	24	\$16,000	\$384,000	\$0.36					
Sterile Filters	m ²	150	\$500	\$75,000	\$0.07	m ²	150	\$500	\$75,000	\$0.07	m ²	150	\$500	\$75,000	\$0.07
Total Consumables				\$9,855,000	\$9.21				\$459,000	\$0.43				\$75,000	\$0.07

Supplementary Table S7: Variable operating cost utilities

	ATF					TFF					Large-Scale Perfusion				
Utilities	Unit	Per year	Unit Cost	\$/y	\$/kg	Unit	Per year	Unit Cost	\$/y	\$/kg	Unit	Per year	Unit Cost	\$/y	\$/kg
Process water	kg	61,006,667	\$0.02	\$1,220,133	\$1.140	kg	61,006,667	\$0.02	\$1,220,133	\$1.140	kg	61,006,667	\$0.02	\$1,220,133	\$1.140
VPSA Power	kWh	2,279,333	\$0.05	\$113,967	\$0.107	kWh	2,279,333	\$0.05	\$113,967	\$0.107	kWh	2,279,333	\$0.05	\$113,967	\$0.107
Compressor power	kWh	116,000	\$0.05	\$5,800	\$0.005	kWh	116,000	\$0.05	\$5,800	\$0.005	kWh	116,000	\$0.05	\$5,800	\$0.005
Agitator power	kWh	26,333	\$0.05	\$1,317	\$0.001	kWh	26,333	\$0.05	\$1,317	\$0.001	kWh	26,333	\$0.05	\$1,317	\$0.001
Chiller power	kWh	1,532,667	\$0.05	\$76,633	\$0.072	kWh	1,532,667	\$0.05	\$76,633	\$0.072	kWh	1,532,667	\$0.05	\$76,633	\$0.072
Dewatering power	kWh	22,000	\$0.05	\$1,100	\$0.001	kWh	22,000	\$0.05	\$1,100	\$0.001	kWh	22,000	\$0.05	\$1,100	\$0.001
Facility power	kWh	17,804,667	\$0.05	\$890,233	\$0.832	kWh	17,804,667	\$0.05	\$890,233	\$0.832	kWh	17,804,667	\$0.05	\$890,233	\$0.832
Natural gas	MMBtu	333	\$2.90	\$966	\$0.001	MMBtu	333	\$2.90	\$966	\$0.001	MMBtu	333	\$2.90	\$966	\$0.001
Municipal WWT	m ³	61,000	\$0.40	\$24,400.00	\$0.023	m ³	61,000	\$0.40	\$24,400.00	\$0.023	m ³	61,000	\$0.40	\$24,400.00	\$0.023
Total utilities				\$2,334,549	\$2.18				\$2,334,549	\$2.18				\$2,334,549	\$2.18

Supplementary Table S8: Fixed operating cost summary

	ATF					TFF					Large-Scale Perfusion				
Batch labor (all shifts)	Attention	h/y	FTE/y	\$/y	\$/kg	Attention	h/y	FTE/y	\$/y	\$/kg	Attention	h/y	FTE/y	\$/y	\$/kg
Seeding prep	8 h	2,400	2	\$100,435	\$0.09	8 h	2,400	2	\$100,435	\$0.09	8 h	2,400	2	\$100,435	\$0.09
Media prep	2 h / change	20,000	10	\$502,174	\$0.47	2 h / change	20,000	10	\$502,174	\$0.47	2 h / change	20,000	10	\$502,174	\$0.47
Production monitoring	10% time	26,280	13	\$652,826	\$0.61	10% time	10,512	7	\$351,522	\$0.33	10% time	2,102	2	\$100,435	\$0.09
Total batch workers		48,680	25.0	\$1,255,435	\$1.17		32,912	19.0	\$954,130	\$0.89		24,502	14.0	\$703,043	\$0.66
Continuous labor	Positions/shift		FTE/shift			Positions/shift		FTE/shift			Positions/shift		FTE/shift		
Dewatering	0.25 / train		0.5	\$25,000	\$0.02	0.25 / train		0.5	\$25,000	\$0.02	0.25 / train		0.5	\$25,000	\$0.02
Utilities	1		1.0	\$50,000	\$0.05	1		1.0	\$50,000	\$0.05	1		1.0	\$50,000	\$0.05
Maintenance	0.5 / train		2.0	\$100,000	\$0.09	0.5 / train		1.0	\$50,000	\$0.05	0.5 / train		1.0	\$50,000	\$0.05
Supervisor	1 per 10 FTE		1.0	\$70,000	\$0.07	1 per 10 FTE		1.0	\$70,000	\$0.07	1 per 10 FTE		1.0	\$70,000	\$0.07
Total continuous workers			4.5	\$245,000	\$0.23			3.5	\$195,000	\$0.18			3.5	\$195,000	\$0.18
Total workers (all shifts)			43	\$2,235,435	\$2.09			33	\$1,734,130	\$1.62			28.00	\$1,483,043	\$1.39
Labor burden (25%)				\$558,859	\$0.52				\$433,533	\$0.41				\$370,761	\$0.35
Total Labor				\$2,794,293	\$2.61				\$2,167,663	\$2.03				\$1,853,804	\$1.73

Supplementary Table S9: Total cost of production summary Serum-Free Medium (SFM)

	ATF		TFF		Large-Scale Perfusion	
	\$/y	\$/kg	\$/y	\$/kg	\$/y	\$/kg
Nutrients (SFM)	\$80,876,060	\$75.58	\$80,876,060	\$75.58	\$80,876,060	\$75.58
Consumables	\$9,855,000	\$9.21	\$459,000	\$0.43	\$75,000	\$0.07
Utilities	\$2,334,549	\$2.18	\$2,334,549	\$2.18	\$2,334,549	\$2.18
Total variable OPEX	\$93,065,609	\$86.97	\$83,669,609	\$78.19	\$83,285,609	\$77.83
Burdened labor cost	\$2,794,293	\$2.61	\$2,167,663	\$2.03	\$1,853,804	\$1.73
Annual maintenance	\$4,955,842	\$4.63	\$2,523,362	\$2.36	\$1,613,727	\$1.51
Annual insurance	\$6,194,803	\$5.79	\$3,154,203	\$2.95	\$2,017,159	\$1.89
Total fixed OPEX	\$13,944,939	\$13.03	\$7,845,229	\$7.33	\$5,484,690	\$5.13
Total cost of wet biomass production	\$107,010,548	\$100.00	\$91,514,837	\$85.52	\$88,770,299	\$82.96
Total cost of product (USD/kg)		\$53.00		\$45.76		\$44.48
Total cost of product (USD/lb)		\$23.98		\$20.71		\$20.13

Supplementary Table S10: Total cost of production summary Animal Component-Free Medium (ACF)

	ATF		TFF		Large-Scale Perfusion	
	\$/y	\$/kg	\$/y	\$/kg	\$/y	\$/kg
Nutrients (SFM)	\$15,104,086	\$14.11	\$15,104,086	\$14.11	\$15,104,086	\$14.11
Consumables	\$9,855,000	\$9.21	\$459,000	\$0.43	\$75,000	\$0.07
Utilities	\$2,334,549	\$2.18	\$2,334,549	\$2.18	\$2,334,549	\$2.18
Total variable OPEX	\$27,293,635	\$25.51	\$17,897,635	\$16.73	\$17,513,635	\$16.37
Burdened labor cost	\$2,794,293	\$2.61	\$2,167,663	\$2.03	\$1,853,804	\$1.73
Annual maintenance	\$4,955,842	\$4.63	\$2,523,362	\$2.36	\$1,613,727	\$1.51
Annual insurance	\$6,194,803	\$5.79	\$3,154,203	\$2.95	\$2,017,159	\$1.89
Total fixed OPEX	\$13,944,939	\$13.03	\$7,845,229	\$7.33	\$5,484,690	\$5.13
Total cost of wet biomass production	\$41,238,574	\$38.54	\$25,742,863	\$24.06	\$22,998,325	\$21.49
Total cost of product (USD/kg)		\$22.27		\$15.03		\$13.75
Total cost of product (USD/lb)		\$10.08		\$6.80		\$6.22

Supplementary Table S11: *Gallus gallus* (Chicken) qRT-PCR primer sequences

Gene	Forward Primer	Reverse Primer
<i>TPM-1</i>	qGgaCEP0015616 Assay ID (Bio-Rad)	
<i>FSP1</i>	5'- CCTACAGAAGCAGATGGATGAG -3'	5'- CGCGGAAGAACTCGTTGTA -3'
<i>ITGB3</i>	5'- CTCTTACTTCCCTGTCCCATTAC -3'	5'- GACAGGTCCATCAGGTAGTAGA -3'
<i>COL8A1</i>	5'- AGAGAAACACACGGCGATAC -3'	5'- GGAAGTGCCAGGGAGATTATAG -3'
<i>RPL32</i>	5'- AAGAAGTTCATCCGCCACCA -3'	5'- GAACCTCCTGCGAACTCTGT -3'