DESIGN AND DEVELOPMENT OF AN AUTOMATED CONTINUOUS HARVESTING SYSTEM FOR MICROALGAE PHOTOBIOREACTORS

GROUP 9: UFPR - FSU FIPSE TEAM
PRESENTATION DATE: NOVEMBER 17, 2015

PRESENTERS:

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BEN BAZYLER

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SPONSOR:

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TEAM 9 – TEAM MEMBER NAMES AND ROLES

- Kaelyn Badura[1,2] - UFPR Team Lead
- Yuri Lopes[1] - FSU Team Lead
- Ben Bazyler[1] - Finance and Inventory Manager
- Courtnie Garko[1] - Scale and Process Engineer
- Benalle Lemos[2] - Hydraulics Specialist
- Tomas Solano[1,2] - Lead Mechanical Engineer

[1]Florida State University, Tallahassee, Florida, USA; [2]Federal University of Paraná, Centro - Curitiba, Paraná, Brazil

Presenter: Courtnie Garko

PROJECT OVERVIEW

Goal Statement:

Design of an automated and continuous harvesting system for microalgae for increased biomass production.

Fig 1. Industry scale microalgae photobioreactor at NPDEAS (UFPR), Curitiba, Brazil.

Presenter: Courtnie Garko

BACKGROUND INFORMATION - MICROALGAE

- Research in potential biodiesels such as soybeans, animal fats, and vegetable oils have opened a large field of study and mass production into these alternative natural fuel sources.

- Microalgae
  - High growth rate
  - Minimal usage of land
  - Potential to recycle and clarify used water

- Biomass is a value added product
  - Food stock
  - A source for dyes
  - Medical applications

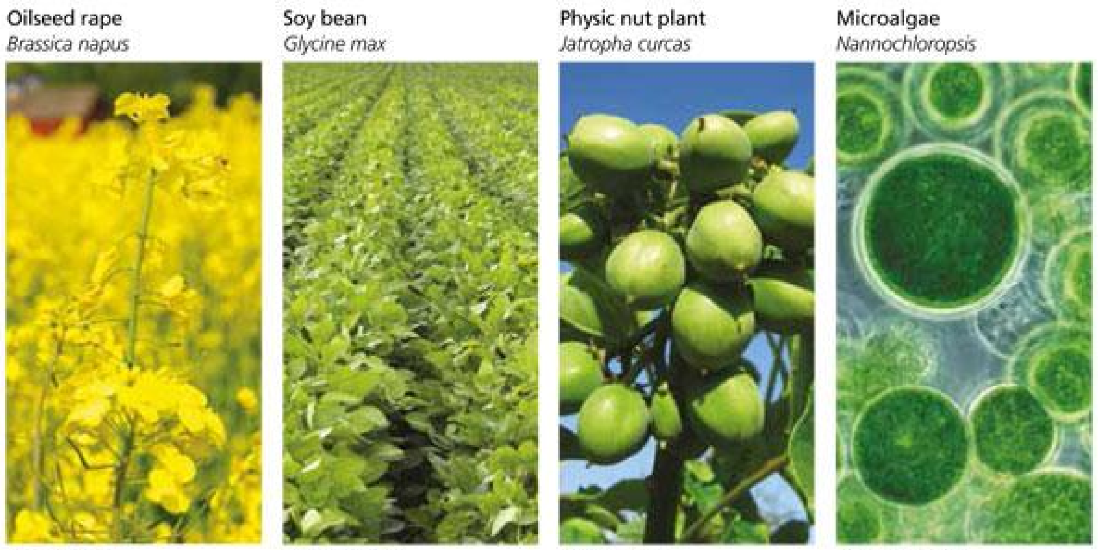

Fig 2. Image showing a select of various alternative crops for alternative production.

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Crop	Oil yield (L/ha)	Land area needed (M ha)[a]	Percent of existing US cropping area[a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1190	223	122
Jatropha	1892	140	77
Coconut	2689	99	54
Oil palm	5950	45	24
Microalgae[b]	136,900	2	1.1
Microalgae[c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.

YIELD AND LAND USAGE OF OIL CROPS

Fig 3. table of various oil crops, their oil yield, land area required for yield, and its relative consumption of of existing cropping area (Christi, 2007).

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BACKGROUND INFORMATION - CULTIVATION

- Cultivation can be implemented as a closed or an open system.
  - Open - natural bodies of water or artificial ponds
    - Advantages: Ease and cost efficiency of installation and operation
    - Disadvantages: Larger land consumption, contamination, and difficulties with input control
  - Closed - Airlifts and photobioreactors
    - Advantages: Artificially or naturally illuminated, reliable condition control, space efficient
    - Disadvantages: Higher initial capital investment and requires more maintenance

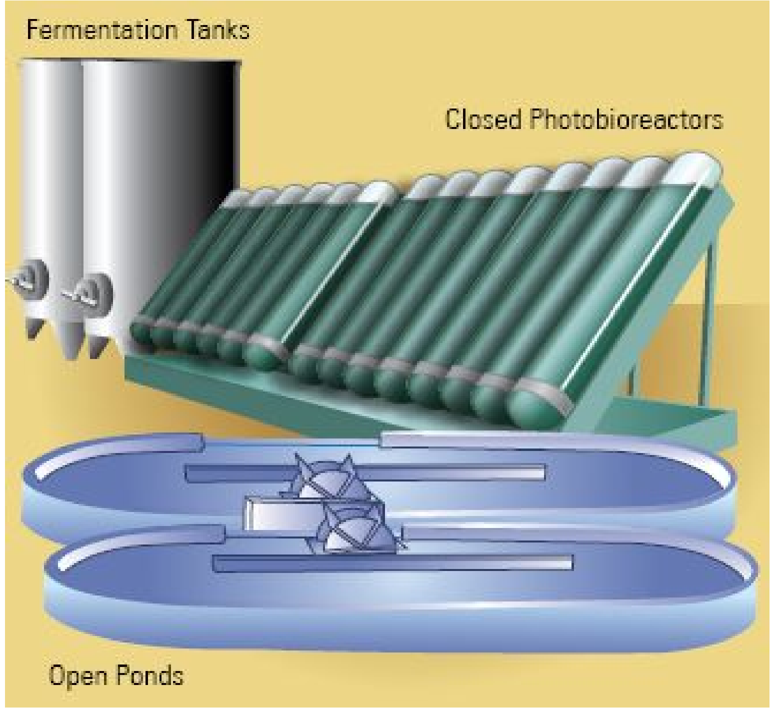

Fig 4. Two closed (PBR, fermentation tank) and one open (raceway pond) algae cultivation systems

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BACKGROUND INFORMATION - HARVESTING

- Harvesting of microalgae is a process which involves flocculation, coagulation, clarification, and extraction.
- Flocculation is the process by which algae cells are modified so they will conglomerate.
- Types of flocculation:
  - Auto-flocculation
  - Chemical flocculation
  - Filtration
  - Centrifugation
  - Electric means- Electroflotation and electroflocculation

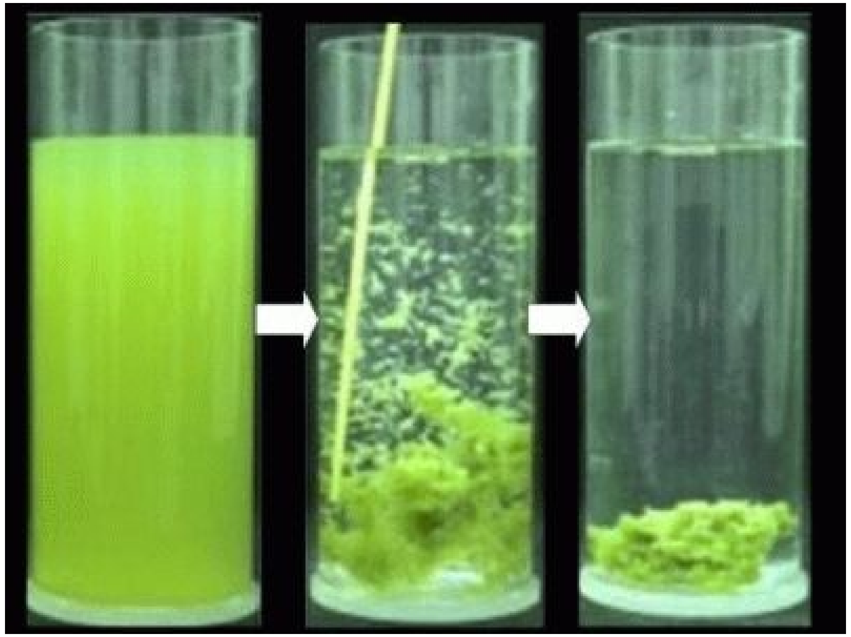

Fig 5. Image showing flocculation of microalgae. Progression of process is left to right.

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BACKGROUND INFORMATION - ELECTRIC SEPARATION

- Electro-flocculation
  - Separation of algae cell from medium

- Pulsed Electric Field Lysis (PEF Lysis)
  - Algae cell lysis; oil extraction and biomass flocculation
  - Pulsed electric fields cause cell poration
  - Reduce post-processing of biomass

KEY TECHNICAL CONSIDERATIONS

- This is a fundamentally interdisciplinary project.
- There are five main technical considerations which will direct the evolution of this project, including:
  - Cultivation process
  - Scalability
  - Harvest 1 gram of biomass per liter of culture
  - Space efficiency optimization
  - Minimal loss system by recycling medium

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PROJECT OBJECTIVES

- Biomass production process must be fully automated.
  - Batch, semicontinuous, and continuous collection.
- Must have ability to separate produced biomass and clarified medium.
- Must minimize energy and resource consumption.
- System must be scalable.
- System will work with different species of algae.

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CONSTRAINTS

- The clarified medium must be recycled.
- The produced biomass must remain usable as biomass is intended for biodiesel.
- The entire system's flow rate will be dictated by the growth rate of the utilized microalgae. The growth rate of each algae is different and therefore the system must be able to adapt.

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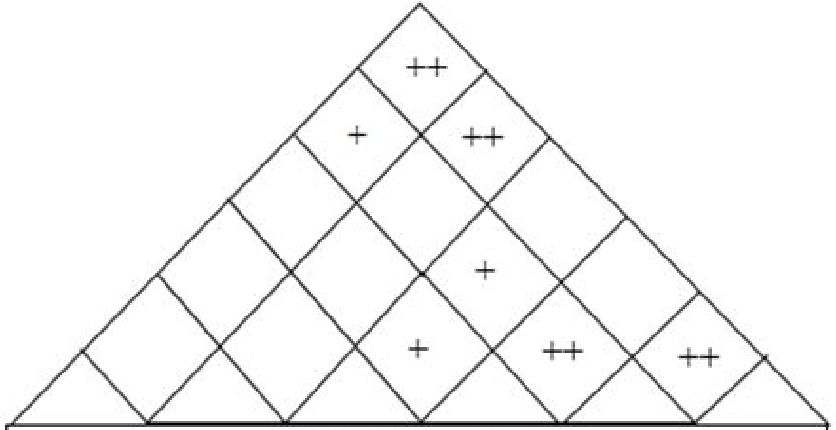
CONCEPT DESIGN : REVISITED

GENERATION AND SELECTION

Presenter: Yuri Lopes

Table 1. House of quality.



Customer Requirements	Importance	Amount of biomass	Resistance to corrosion	Cost of Energy	Micro-Controller Timing	Biomass extraction efficiency	Design of Clarifier	Customer Total	Percentage
		Engineering Characteristics							
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Separate biomass	5	1			3	9	1	70	24.60%
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Continuous Flocculation + Sedimentation	5				9			45	15.80%
Sustainable	3		9	9				54	19.00%
Scalable	2	3					9	24	8.50%
Works with different algae	2	1				3	3	14	4.90%
Total		22	27	32	108	51	44		
Percentage		7.70%	9.50%	11.30%	38.00%	18.00%	15.50%		

Presenter: Yuri Lopes

DESIGN BREAKDOWN

FSU Led Cultivation Initiative

- Medium Component Design
  - Preparation, input parameters
- Cultivation Design
  - Growth
  - Distribution
- Sensor and Automation

UFPR Led Harvesting Initiatives

- Design of Flocculation Process
  - Coagulation
  - Flocculation
- Separation and Extraction of Biomass
- Sensor and Automation

Presenter: Yuri Lopes

CONCEPT DESIGNS

FSU Led Cultivation Initiative

- Composition Sensors
  - Displacement
- Culture Constituent Mixing
  - Aeration
- Structural Design
  - Vertical rectangular container
- Fluid Transfer Mechanism
  - Solenoidal Valve

UFPR Led Harvesting Initiatives

- Coagulative Mixing
  - Static Inline Mixer
- Flocculation
  - Inline Bulb Mixer
- Clarification and Sedimentation
  - Corrugated Angled Lamella Plates
- Extraction
  - Modified peristaltic pump
  - Sludge dewatering mechanism

Presenter: Yuri Lopes

AUTOMATION

FSU Led Cultivation Initiative

- Density Sensor and LED/Transistor pair (refilling)
- Solenoid Valves (transporting)
- Arduino (microcontroller)

UFPR Led Harvesting Initiatives

- 2 Infrared LED’s
  - Looking into potential alternatives
    - Image processing
- Phototransistors
  - Magnitude of light

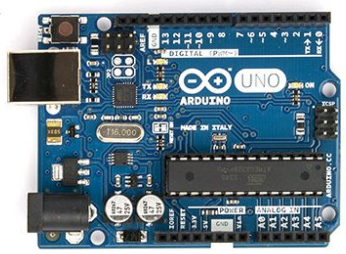

Fig 6 Automation devices::

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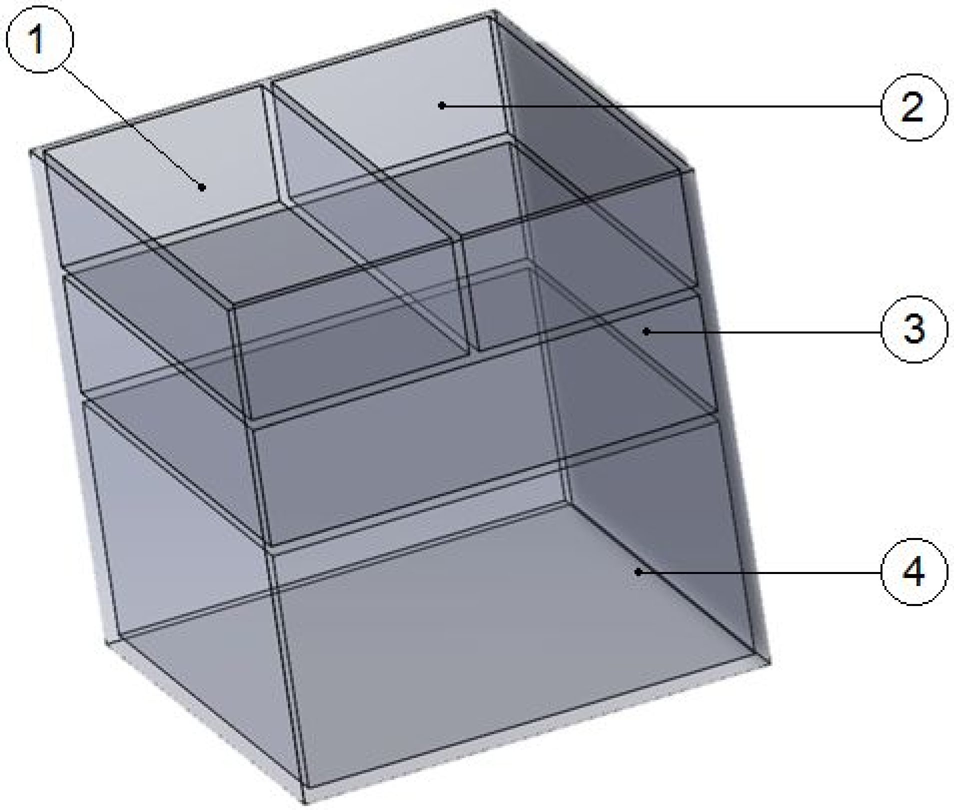

- 1) CHU Medium
- 2) Distilled water
- 3) Medium Component Homogenizer and recycled clarified medium
- 4) Cultivation Tank

CULTIVATION INITIATIVE

Fig 7. Cultivation Enclosure Design Concept CAD Drawing.

Presenter: Yuri Lopes

CULTIVATION PROGRESS - SETUP AND GROWTH

- Purchased Scenedesmus Obliquus Algae and Chu medium
  - Algae supplier: University of Texas

- Setup of cultivation infrastructure
  - Modified Shelf
  - Light fixtures
  - Air pump
  - Hosing

- Cultivation of algae has commenced

Fig 8. Picture of algae setup similar to FSU infrastructure.

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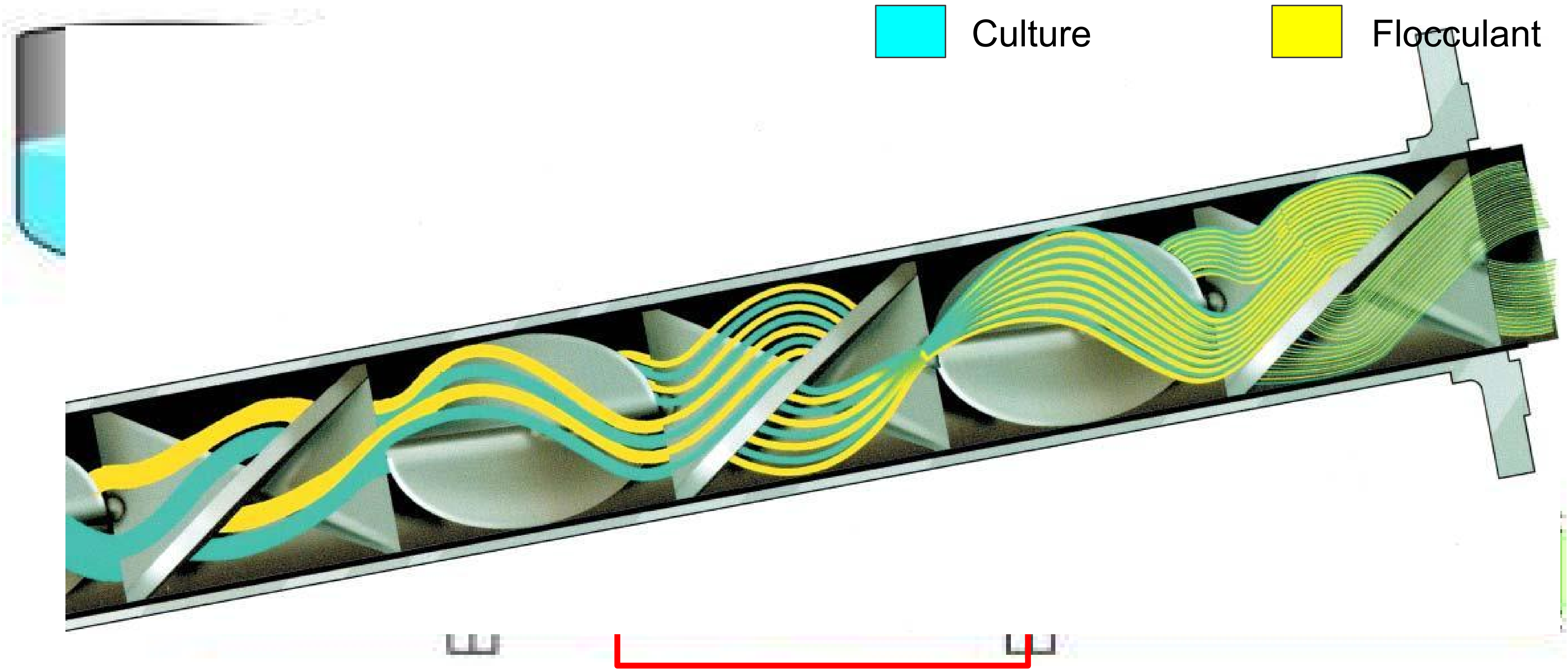


STATIC INLINE MIXING

Fig 9. Visualization of static inline mixing process.

FLOCCULATION - MIXING

Circular bulb mixers will be implemented to promote gentle mixing to allow more uniform formation of clots for more rapid sedimentation upon entranced into the clarifier tank.

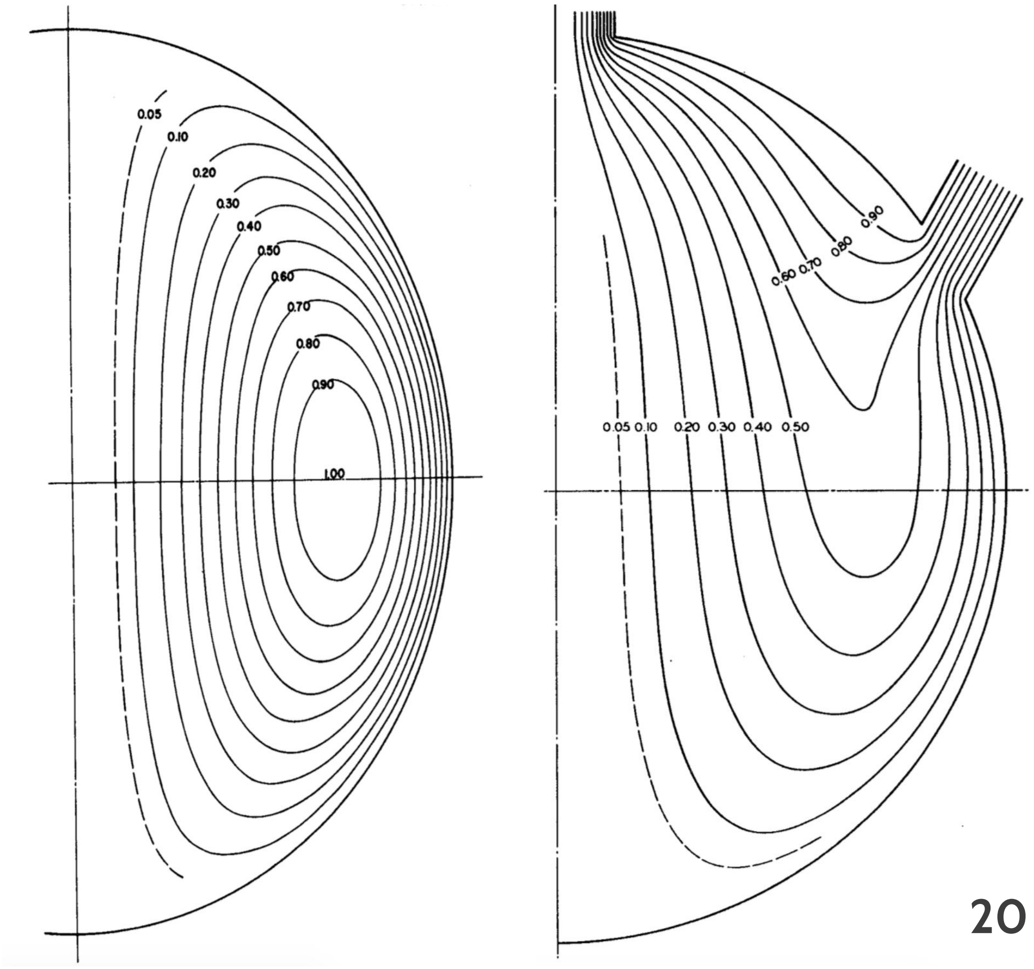
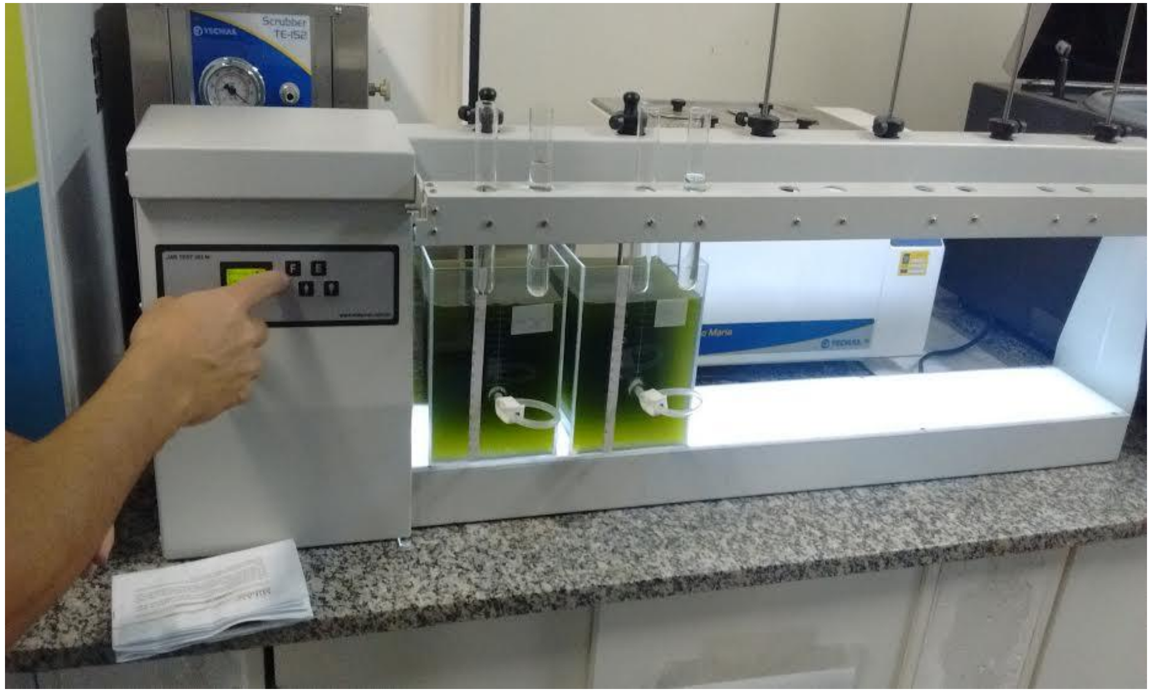


Fig 10. Flow visualization for flow inside of a sphere.

Presenter: Yuri Lopes

FLOCCULANT TESTING

- Testing with three main objectives:
  - Approximate settling time
  - Approximate sedimentation velocity
  - Investigate correlation between flocculant concentration and effectiveness
- Flocculant was tested
  - Tanfloc



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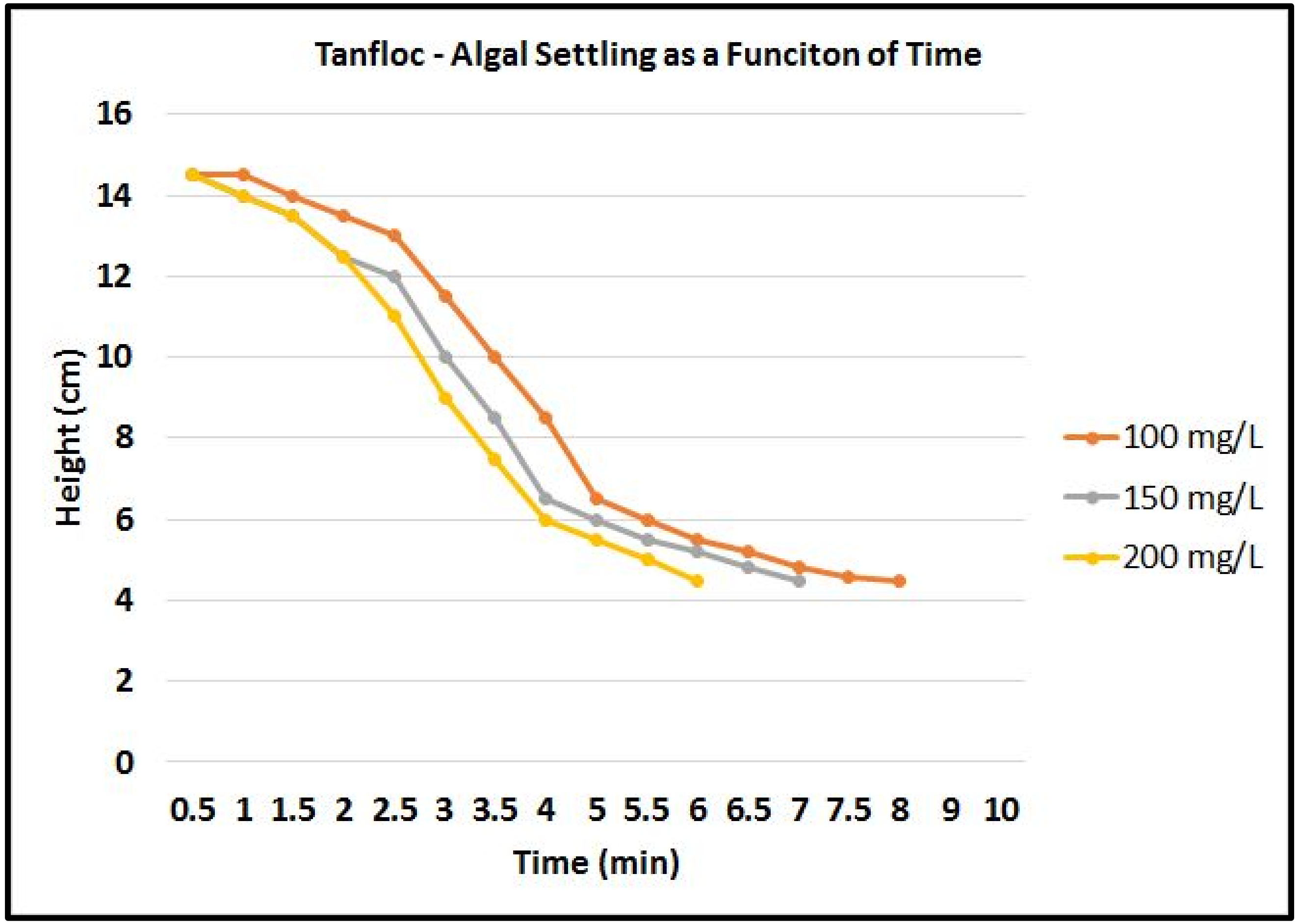

TANFLOC			
Concentrations ($mg \cdot L^{-1}$)	100	150	200
Clarity *	2.5	1	1
Sedimentation Velocity ($cm \cdot s^{-1}$)	0.0151	0.0195	0.0205

***NOTE(S)**:

- Clarity is classified from 1 (low turbidity) to 5 (high turbidity).

TANFLOC TESTING RESULTS

Fig 11. Visualization of static inline mixing process.

Table 12. Table of Tanfloc testing results including test concentrations, final water clarity, and sedimentation velocity.

Presenter: Yuri Lopes

Cost comparison for different separation processes.

Separation processes	Reference	Year	Cost ($\$kg^{-1}$ biomass) Original[c]	2012	Items included in the processing cost
Centrifugation – self cleaning plate	[3]	1995	1.71	2.58	Plant depreciation, maintenance and energy
	[7]	1988	0.86[a]	1.68	Equipment depreciation, maintenance and energy
Flocculation – sedimentation	[7]	1988	0.37[a]	0.72	Plant depreciation, maintenance, flocculant and energy
	[4]	1996	1.25	1.83	Plant depreciation, maintenance, flocculant and energy
Flocculation – flotation	[3]	1995	1.39	2.10	Plant depreciation, maintenance, flocculant and energy
	[7]	1988	0.91[a]	1.78	Plant depreciation, maintenance, flocculant and energy
Electro-flocculation	[9]	1997	0.22	0.31	Energy only
Microbial flocculation	[21]	2010	0.29[b,d]	0.31	Plant depreciation, maintenance, raw materials and energy
Electro-flocculaiton		2012		0.19	Plant depreciation, electrode dissolution and energy

[a] US $1 = DM 1.85 in 1988.
[b] US $1 = A $1.1 in 2010.
[c] US consumer price index in 1988, 1995, 1996, 1997, 2009 and 2012 are 115.7, 150.3, 154.4, 159.1, 211.1 and 226.6 respectively.
[d] Typical biomass concentration is assumed to be 0.5 kg m^{-3}.

EVALUATION OF FLOCCULATION

Fig 13. Cost comparison of different flocculation processes.

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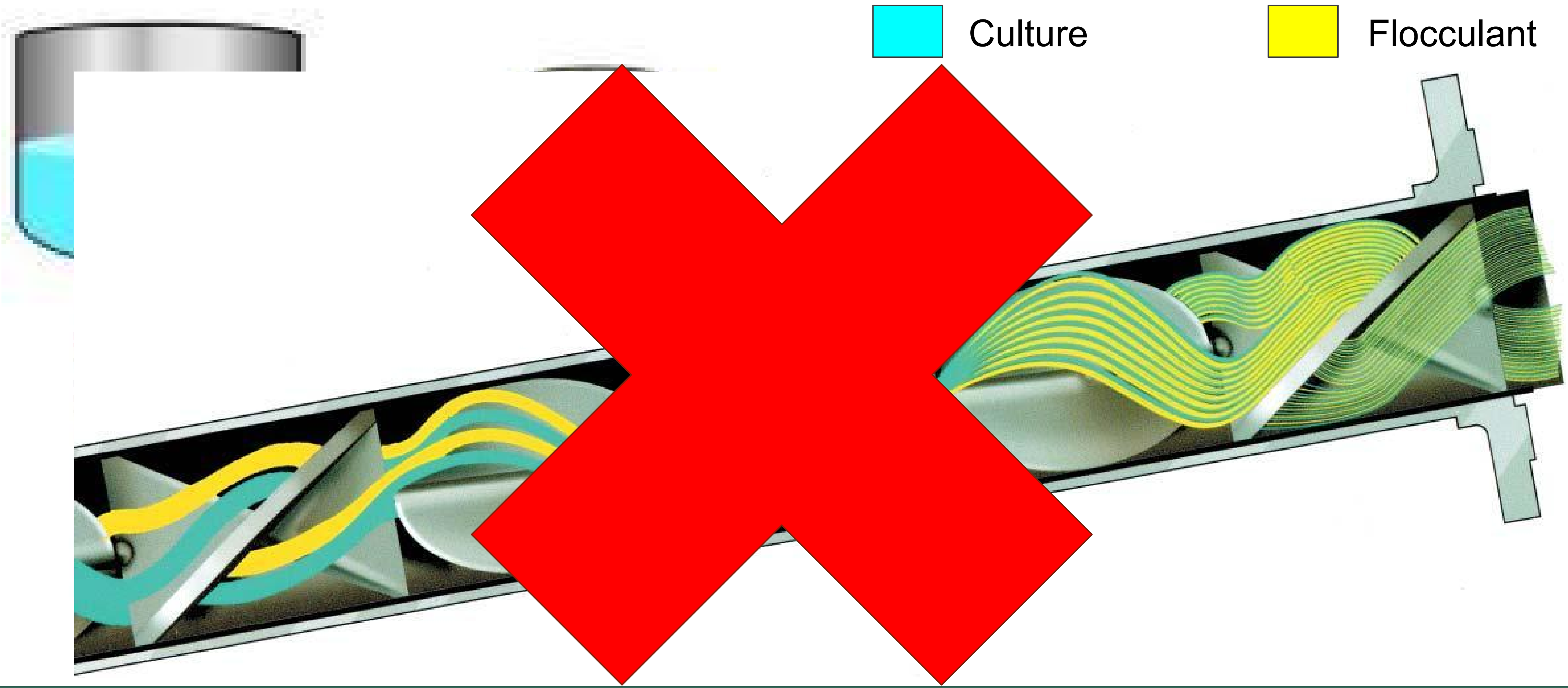
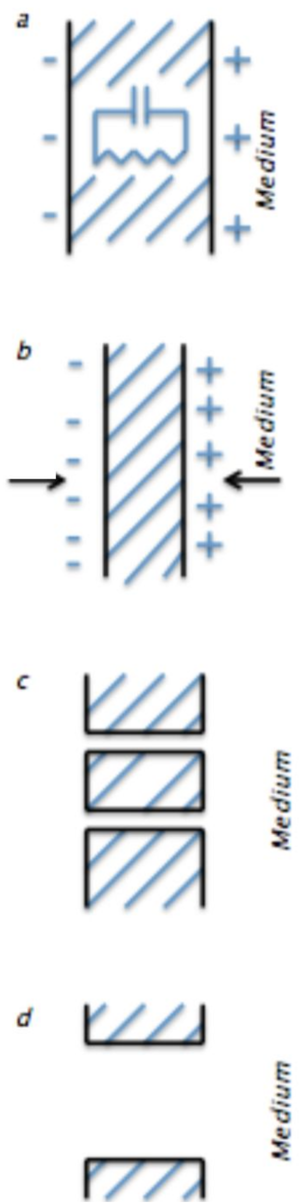


STATIC INLINE MIXING

Fig 14. Visualization of static inline mixing process.

PULSED ELECTRIC FIELD



a. The cell membrane under the Home Potential (R) (equivalent circuit represented in the membrane)

b. External Electric Field (E) increases the potential of the membrane, causing compression of the membrane.

c. A further increase in the external electric field leads to the critical potential of the membrane and subsequent formation of pores.

d. If the external electric field becomes too large, large pores will be formed.

Fig 15. Pulsed Electric Field Process.

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PULSED ELECTRIC FIELD LYSING

- Requires low energy expenditure
- Capacitors are charged and discharged to create the pulsed electric fields
- Governed by microcontroller

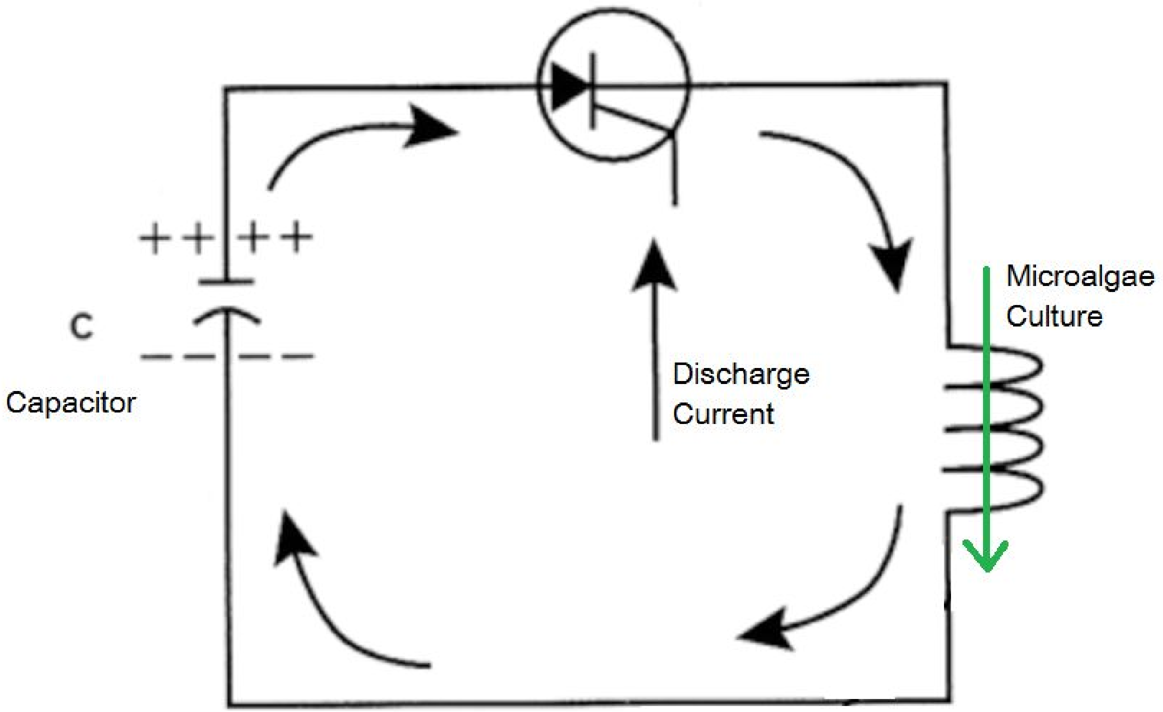

Fig 16. System schematic of pulsed electric field lysis.

Presenter: Ben Bazyler

PULSED ELECTRIC FIELD LYSING

- Lysing the algae cells will cause the oil and organelles to leak out.
- Oil extraction and biomass sedimentation become one process.
- Removes the additional need for centrifugation and additional manual or chemical oil extraction process after flocculation.

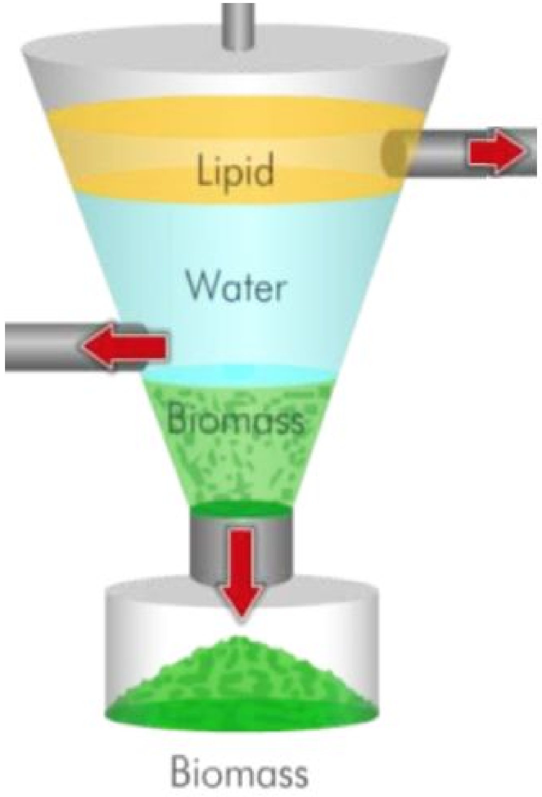

Fig 17. Visual representation of intended results of pulsed electric field lysis.

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Presenter: Ben Bazyler

MATHEMATICAL MODEL AND EXPERIMENTS FOR PEF LYSIS DESIGN

Empirical Tests

- Several experiments will be conducted to validate the model.
  - Efficiency, feasibility etc.
- An equivalent jar test for settling velocity of the lysed cells will be conducted as well to ensure proper clarifier dimensionalizing.

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MATHEMATICAL MODEL

- Based on the assumptions listed, process efficiency can be defined as:

$$\eta = \frac{N_{lys}}{2 \cdot N_0}$$

Where, N_{lys} is the number of lysed cells
N_0 is the number of initial whole cells

- A transient model will be created to find the response time needed to reach steady state.
- A system of differential equations, based on the dimensionless mass of each lysed and whole cell system, is to be solved to obtain the maximum flow rate for complete lysis (~95%).

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} + \mu$$

Where, the lysis rate μ is a function of mass flow rate, time, and PEF energy. To be determined through literature or empirically.

- Note – μ is expected to be a step function due to the pulsed nature of the applied field.

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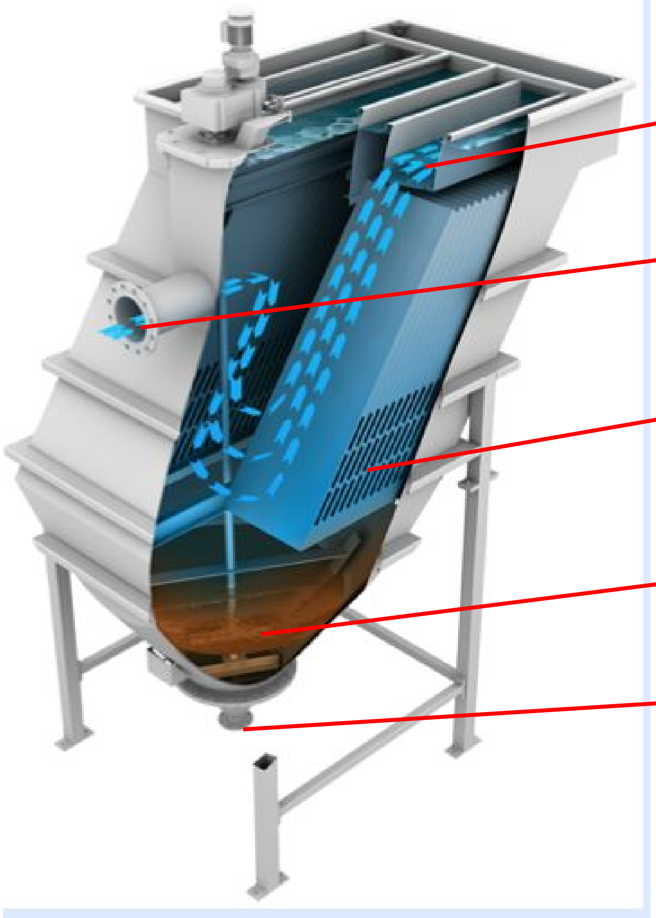

Dam - discharge outlet of the clarified medium

Entry - From flocculation stage

Lamellas - corrugated to increase surface area

Sludge Blanket

Extraction / dehydration - modified peristaltic pump

CLARIFICATION AND SEDIMENTATION

Fig 18. Representation of a basic lamella separator.

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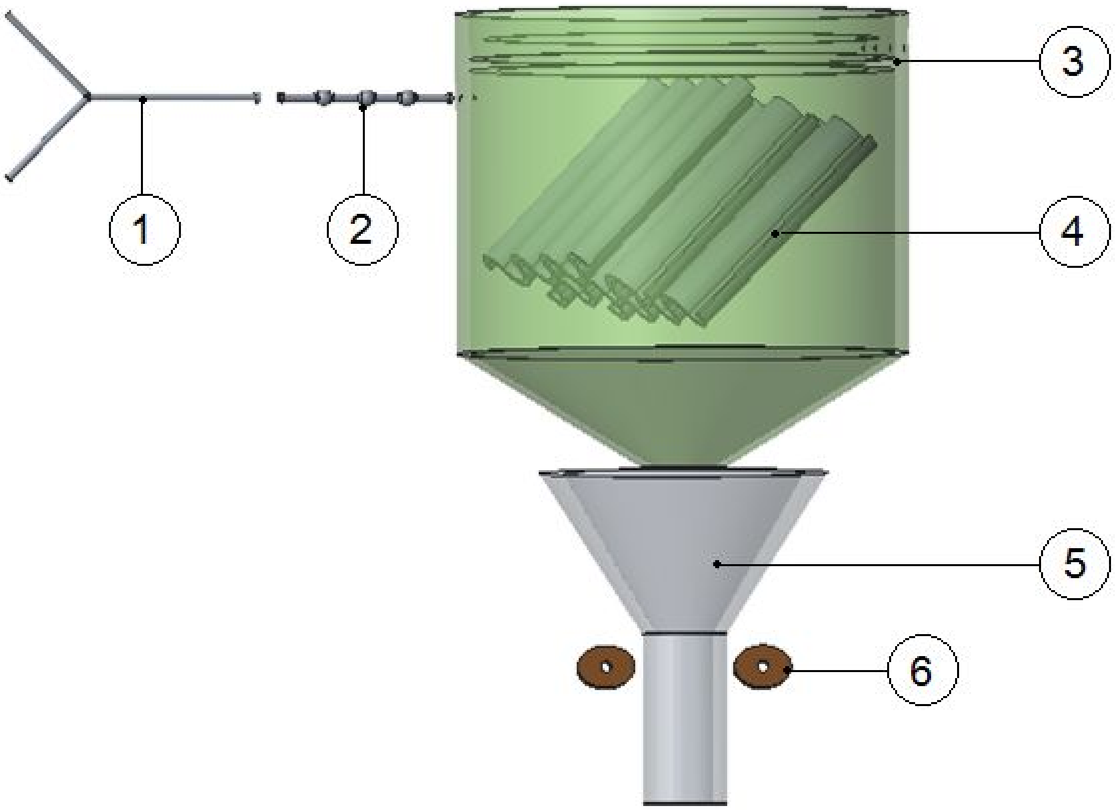

- 1) Static Inline Mixer
- 2) Inline Bulb Mixer
- 3) Clarifier Tank
- 4) Angled Lamella Assembly
- 5) Flexible Dewatering Extraction Channel
- 6) Modified peristaltic pump

Fig 19 Harvesting Assembly Design Concept CAD Drawing.

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RISK AND CHALLENGE IDENTIFICATION

FSU Culture Initiative

- Light and CO_2 distribution in larger scale systems
- Preventing medium evaporation
- Ensuring longevity of live algal cultures

UFPR Harvesting Initiative

- Modeling and designing PEF lysing system components
- Design of a modified peristaltic pump to extract biomass
- Implementation of a flexible sludge dewatering mechanism

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LOGISTICAL CHALLENGES

Current Challenges

- Sustaining algal growth at FSU
- Geographically dispersed team
- Optimization of pulsed electroflocculation

Potential Challenges

- Sanitation and use of current photobioreactor skeleton
- Separate prototype development
- Development of numerical system models

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FUTURE PLANS

FSU TEAM

- Finish designing and selecting the harvesting components
- Maintain project budget and inventory of supplies
- Continue to cultivate algae
- Begin small prototype build
  - Purchase and test sensors

UFPR TEAM

- Finish dimensionalizing clarifier tank
- Electroflocculation tests and optimization
  - Mathematical model of electroflocculation efficiency as a function of time and applied voltage
- Lamella structures characterization
- Flocculator and clarifier prototype design

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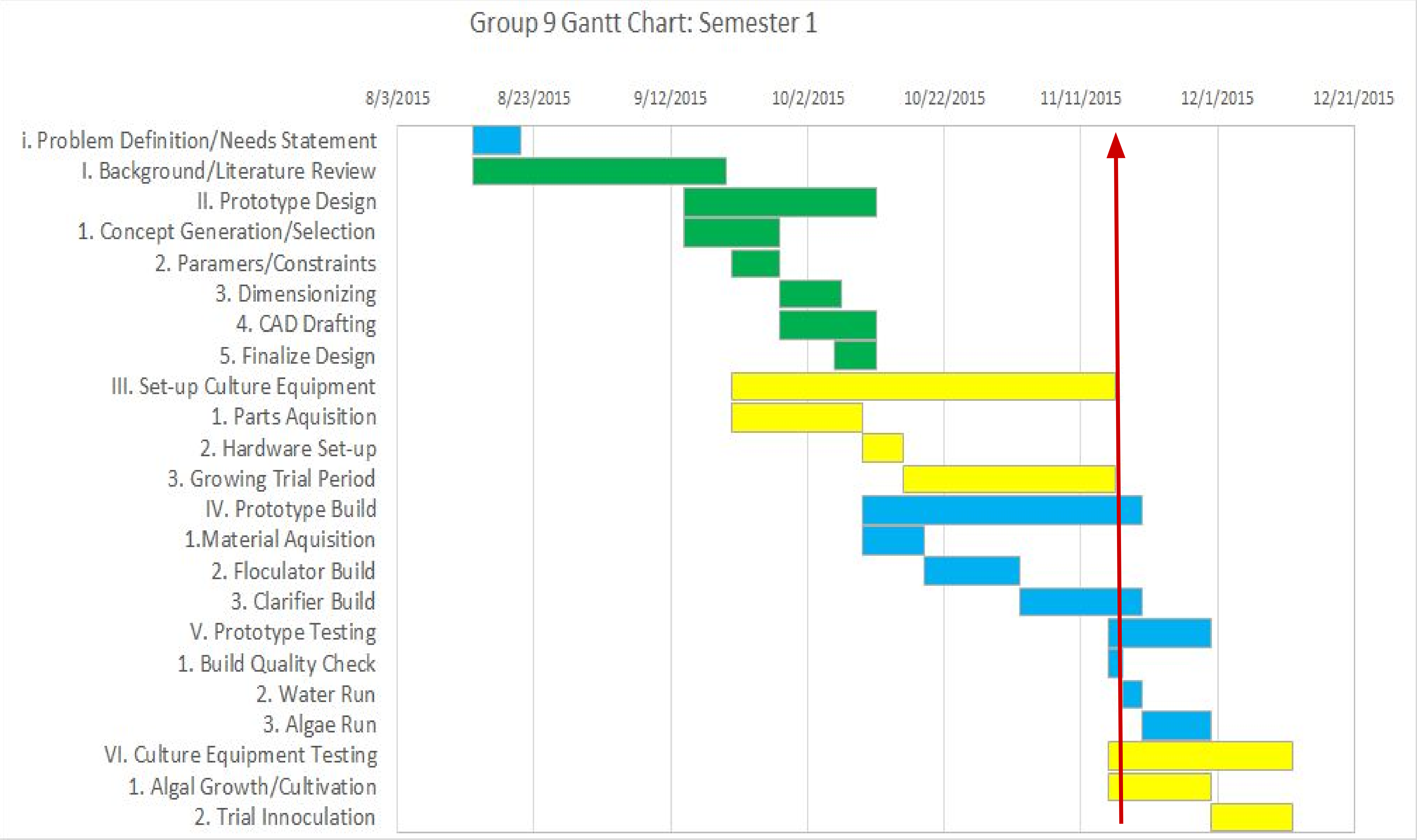

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SUMMARY

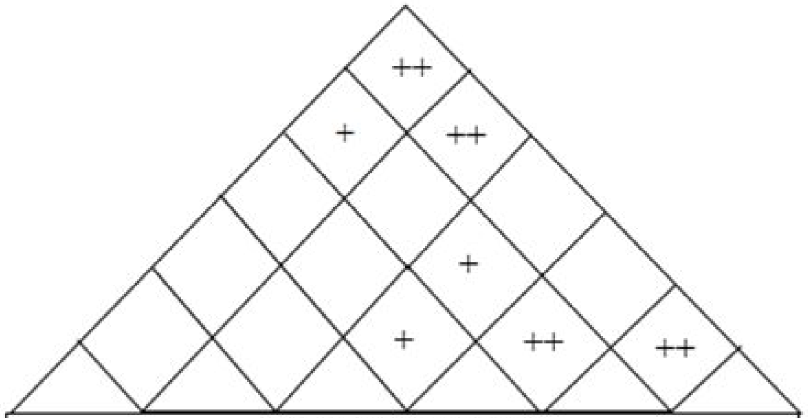
Component designs evaluated and selected based on needs and project objectives.

- Cultivation: Optimize efficiency and foster sustainable growth
  - Gravity and air pump to minimize moving parts and power
  - Solenoid valve and displacement sensor for automation of medium inputs
- Harvesting: Increase production and space efficiency, decrease production time
  - Pulsed electric field lysing will be used to flocculate biomass and extract oil
  - Lamella clarifier will be optimized based on shape and surface area
  - Peristaltic pump will be used in conjunction with flexible dewatering extraction channel

Presenter: Ben Bazyler

Appendices

Appendix A: House of Quality



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	Total	22	27	32	108	51	44		
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Appendix B:
Medium Preparation and Cultivation Concept Generation

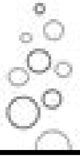
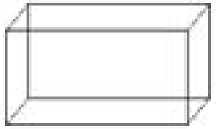
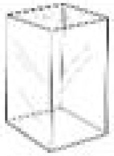
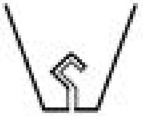
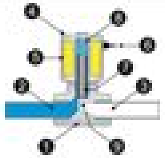
Option	Solutions		
Function			
Composition Sensors	Volume	Force	Displacement
Mixing			
Structural Design			
Transferring Fluid			

Fig B-1. General morphological chart showing all generated component designs

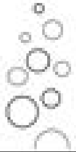
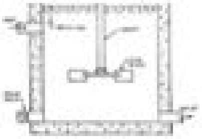
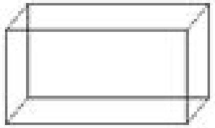
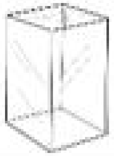
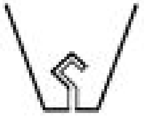
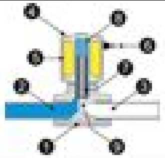
Option 1	Solutions		
Function			
Composition Sensors	Volume	Force	Displacement
Mixing			
Structural Design			
Transferring Fluid			

Fig B-2. Morphological chart showing all selected components for option 1

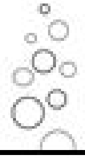
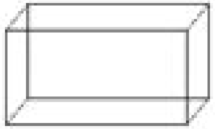
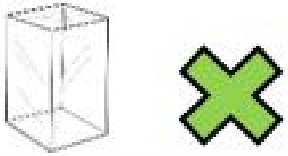
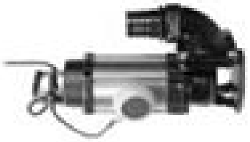
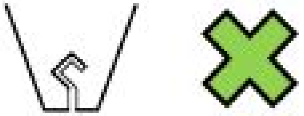
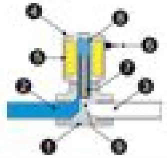
Option 3	Solutions		
Function			
Composition Sensors	Volume	Force	Displacement
Mixing			
Structural Design			
Transferring Fluid			

Fig B-3. Morphological chart showing selected components for option 3, a third possibility

Function: Composition Sensors	Criteria					
Solutions (Weight)	**Cost (2)**	**Size (1)**	**Power (2)**	**Effectiveness (3)**	**Implementation (2)**	**Total**
1. Mass flow rate sensor	1	8	9	8	7	33
Volume	2	8	18	24	14	**66**
2. Force sensor (mat)	5	5	8	6	4	28
Force	10	5	16	18	8	**57**
3. Displacement sensor	10	9	9	6	8	42
Displacement	20	9	18	18	16	**81**

Fig B-4. Decision matrix for composition sensors

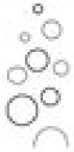
Function: Mixing (Medium)	Criteria					
Solutions (Weight)	Cost (2)	Size (1)	Power (2)	Maintanence (2)	Implementation (3)	Total
1. Static Inline Mixer	3	5	10	10	6	34
	6	5	20	20	18	**69**
Air pump	9	7	6	8	8	38
	18	7	12	16	24	**77**
Mechanical Mixer	2	4	4	3	4	17
	4	4	8	6	12	**34**

Fig B-5. Decision matrix for a mixing mechanism

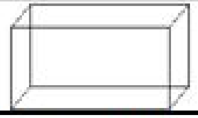
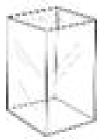
Function: Structural Design	Criteria					
Solutions (Weight)	Cost (2)	Size (2)	Effectiveness (1)	Maintanence (2)	Implementation (3)	Total
1. Erlenmeyer Flasks	2	6	5	8	5	26
	4	12	5	16	15	**52**
2. Horizontal Tank	6	7	5	4	5	27
	12	14	5	8	15	**54**
3. Vertical Tank	6	8	9	4	5	32
	12	16	9	8	15	**60**

Fig B-6. Decision matrix for structural design

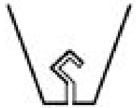
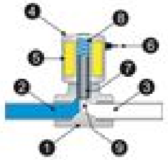
Function: Transferring Fluid	Criteria					
Solutions (Weight)	Cost (2)	Size (2)	Power (2)	Maintanence (1)	Implementation (3)	Total
1. Pump	3	3	2	4	7	19
	6	6	4	4	21	**41**
2. Auto Syphon	9	8	10	8	3	38
	18	16	20	8	9	**71**
3. Solenoid Valve	7	9	8	7	7	38
	14	18	16	7	21	**76**

Fig B-7. Decision matrix for a fluid transfer mechanism

Appendix C:

Harvesting and Extraction Initiative

Concept Generation

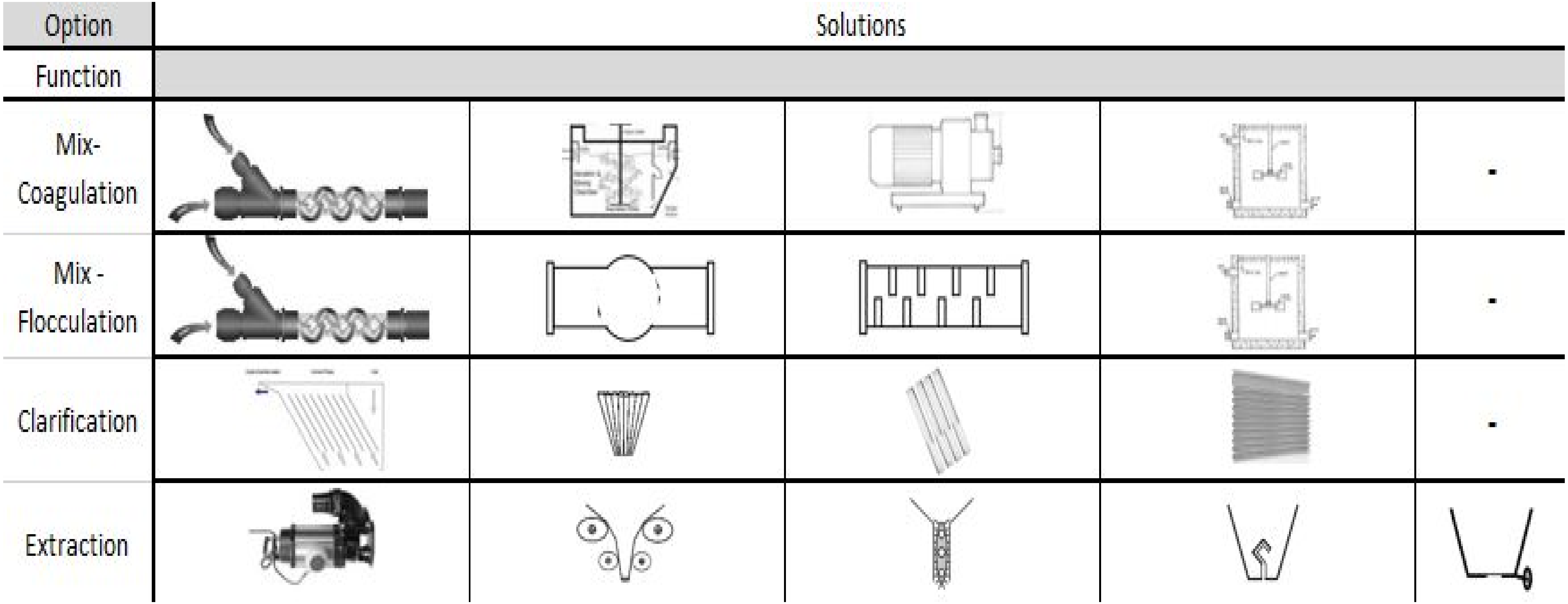


Fig C-1. General morphological chart showing all generated component designs

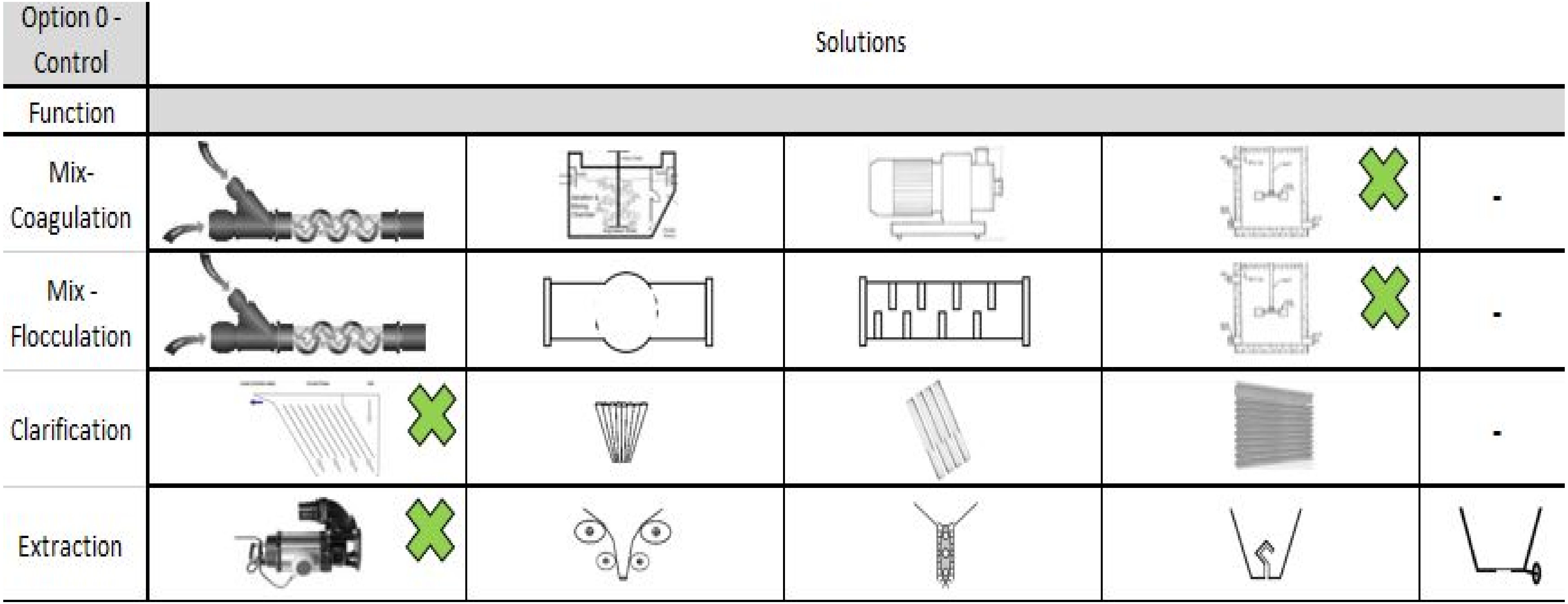


Fig C-2. Morphological chart showing all selected component designs for the control (standard) design

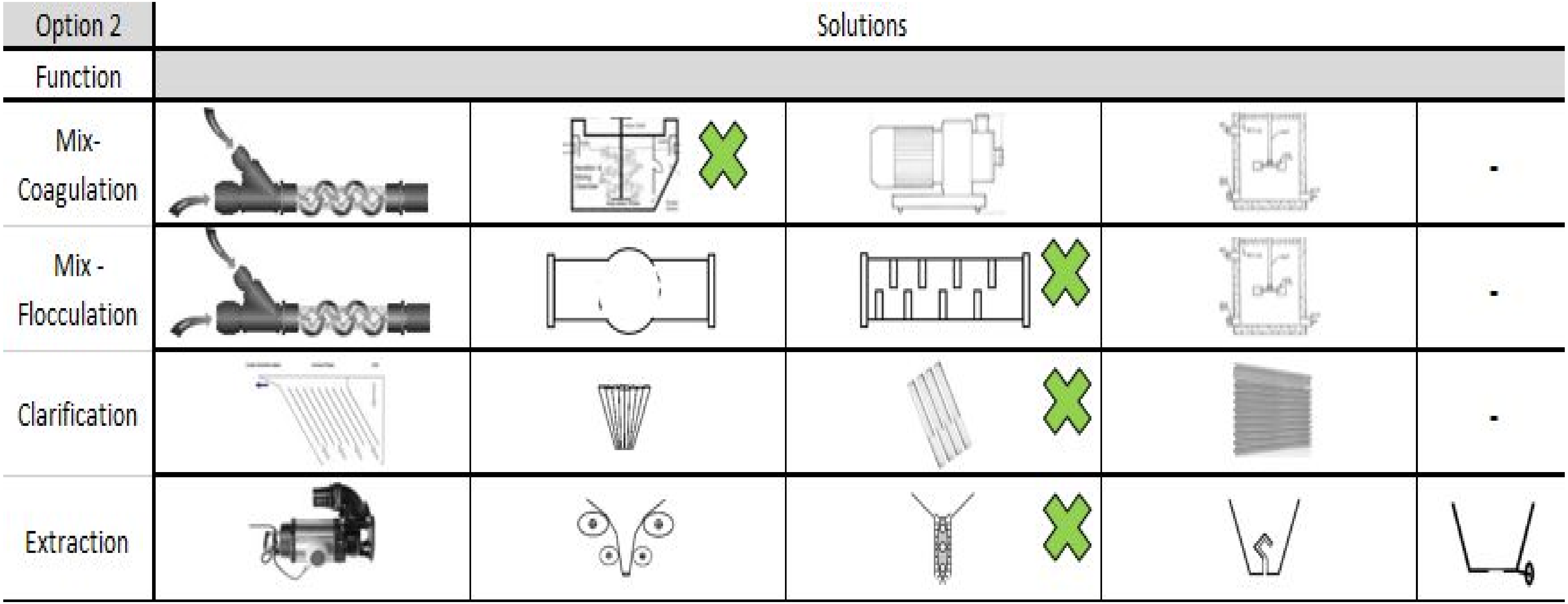


Fig C-3. Morphological chart showing selected component designs for option 2, all components were second highest rated

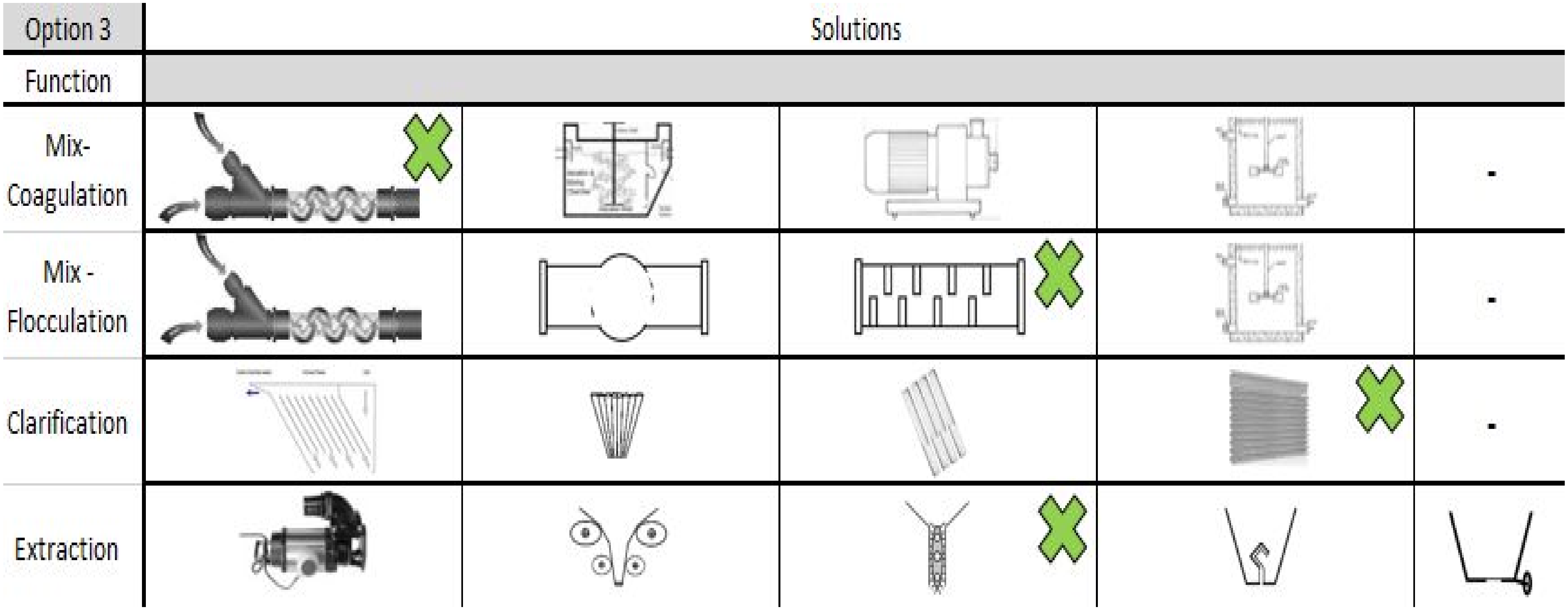


Fig C-4. Morphological chart showing selected component designs for option 3, created from a mixture of option 1 and 2 components

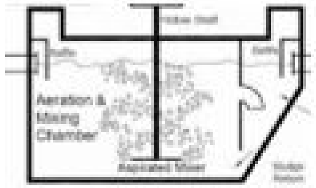
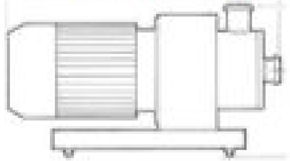
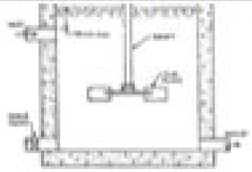
Function: Mixing (Coagulation)	Criteria					
Solutions (Weight)	**Cost (2)**	**Size (1)**	**Power (2)**	**Maintanence (2)**	**Viability (3)**	**Total**
1. Static Inline Mixer	8	9	10	7	6	40
	16	9	20	14	18	**77**
2. Aeration	9	5	6	5	7	32
	18	5	12	10	21	**66**
3. Inline Kinetic Mixer	2	7	4	3	5	21
	4	7	8	6	15	**40**
4. Kinetic Mix Tank	5	5	2	5	9	26
	10	5	4	10	27	**56**

Fig C-5. Decision matrix for component which fulfills function of coagulation- mixing

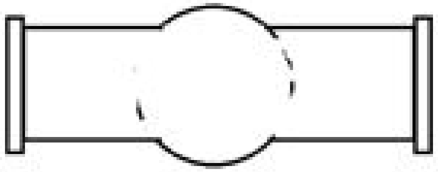
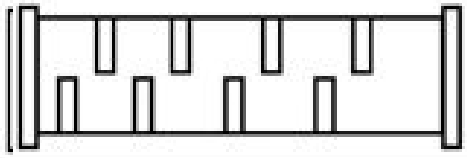
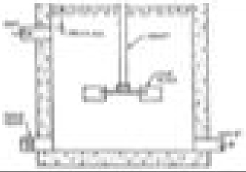
Function: Mixing (Flocculation)	Criteria					
Solutions (Weight)	Cost (2)	Size (1)	Power (2)	Maintanence (2)	Viability (3)	Total
1. Static Inline Mixer	8	9	10	7	6	40
	16	9	20	14	18	**77**
2. Mixing Bulb	9	8	10	8	8	43
	18	8	20	16	24	**86**
3. Baffles	10	9	10	6	8	43
	20	9	20	12	24	**85**
4. Kinetic Mix Tank	5	5	2	5	9	26
	10	5	4	10	27	**56**

Fig C-6. Decision matrix for component which fulfills function of flocculation- mixing

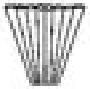
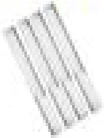
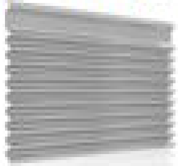
Function: Clarification	Criteria					
Solutions (Weight)	SA (3)	Cost (1)	Implementation (2)	Effectiveness (3)	Novel (1)	Total
1. Parallel Lamella Plates	6	10	10	5	1	32
	18	10	20	15	1	**64**
2. Conical Arrangement Lamella Tubs	5	7	4	7	7	30
	15	7	8	21	7	**58**
3. Parallel Angled Lamella Tubes	9	8	8	8	5	38
	27	8	16	24	5	**80**
4. Parallel Angled Corrugated Lamella Plates	10	7	8	10	7	42
	30	7	16	30	7	**90**

Fig C-7. Decision matrix for component which fulfills function of clarification

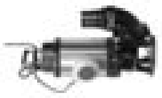
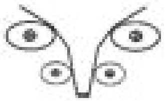
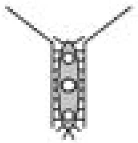
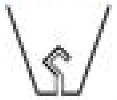
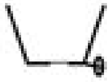
Function: Biomass Extraction	Criteria						
Solutions (Weight)	Cost (2)	Power (1)	Novel (2)	Viability (1)	Maintanence (2)	Effectiveness (2)	Total
1. Pump	1	5	1	10	6	10	33
	2	5	2	10	12	20	**51**
2. Cam Swallow Mechanism	4	6	8	6	4	7	35
	8	6	16	6	8	14	**58**
3. Conveyor/Scrubber	5	6	5	7	4	8	35
	10	6	10	7	8	16	**57**
4. Autosiphon	7	8	5	7	5	2	34
	14	8	10	7	10	4	**53**
4.Free Fall Value	8	8	1	8	8	2	35
	16	8	2	8	16	4	**54**

Fig C-8. Decision matrix for component which fulfills function of extraction

	Baseline	Alternative Solutions		
Criteria	Current Solution	Option 1	Option 2	Option 3
Cost	4	2	1	1
Sustainability	1	1	0	0
Adaptability	3	0	-1	0
Maintanence	2	1	-1	0
Effectiveness	5	1	0	1
∑ Positives	-	16	4	9
∑ Negatives	-	0	-5	0
Total	-	16	-1	9

Fig C-9. Pugh matrix for design configuration evaluation

Appendix D:

Harvesting and Extraction Initiative

CAD Concept Drawings

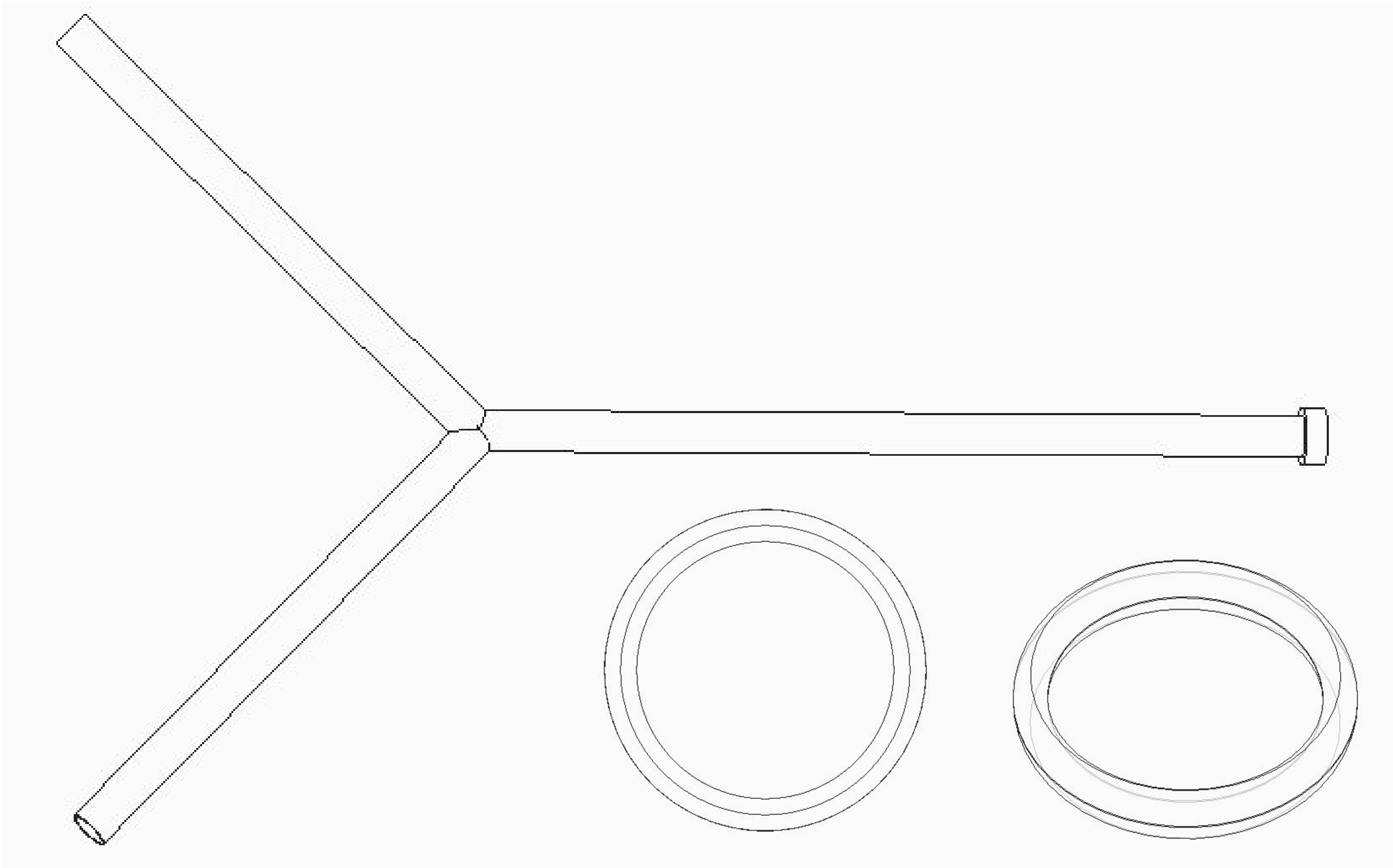


Fig D-1. CAD Drawing for 3 junction static inline mixer and seal used to prevent leaks in piping connections.

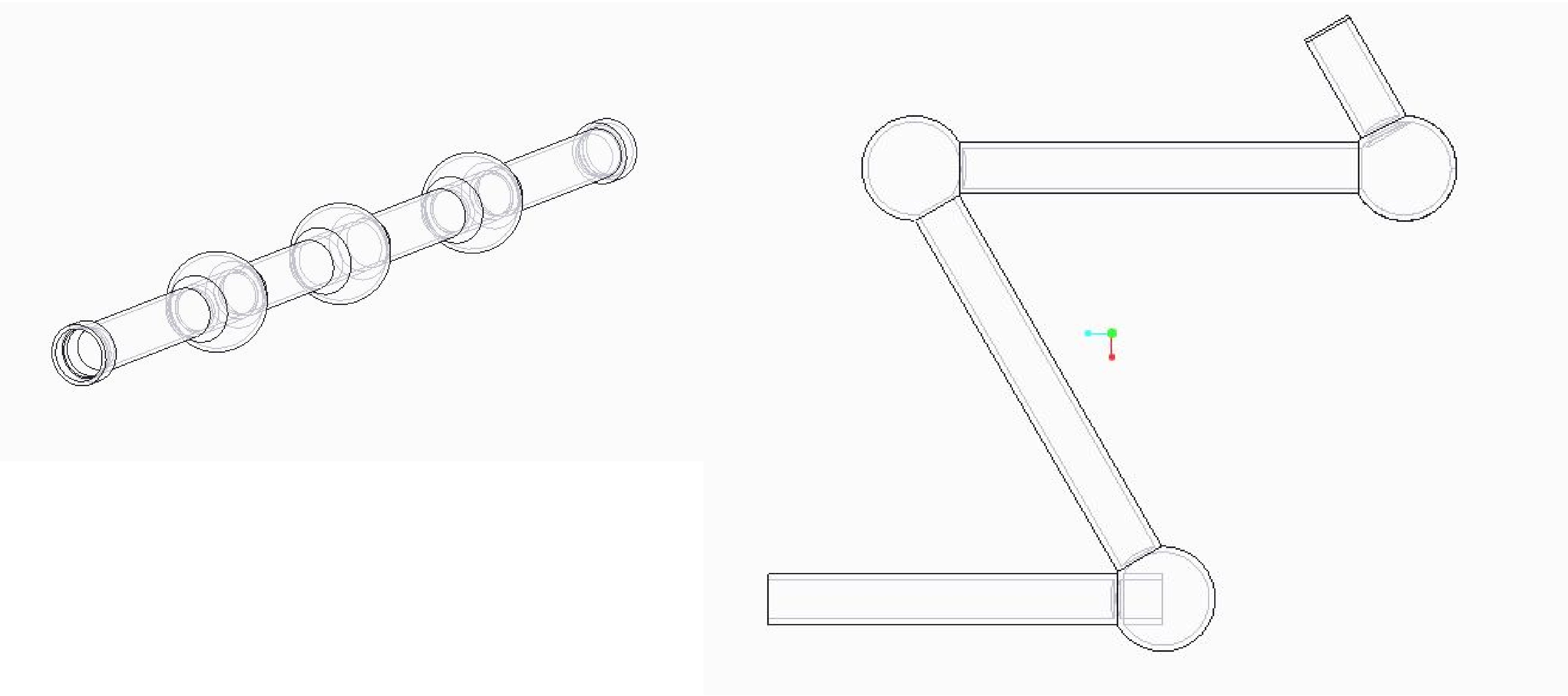


Fig D-2. CAD concept drawings of bulb mixing mechanism.

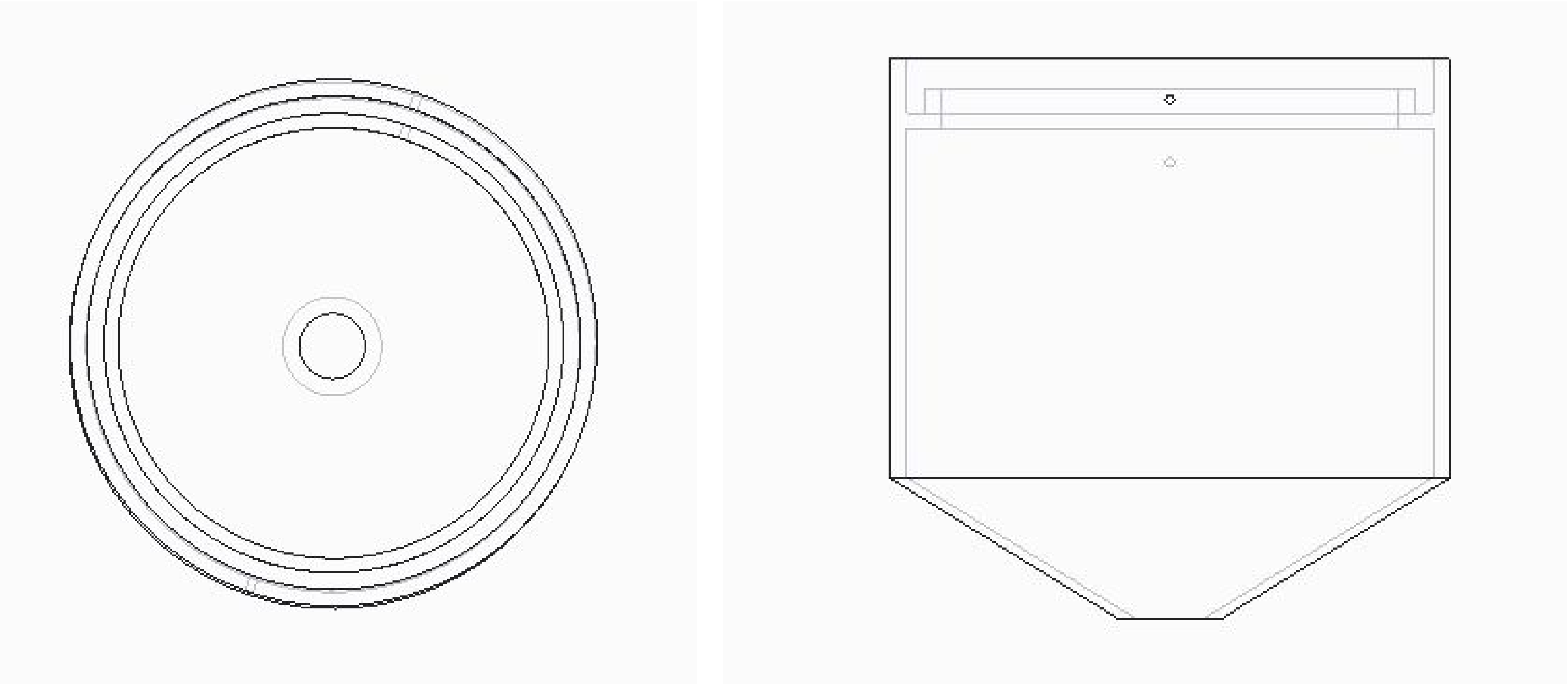


Fig D-3a,b. a. (Left) Top CAD drawing view of conceptual sedimentation tank, b. (Right) Profile view of sedimentation tank.

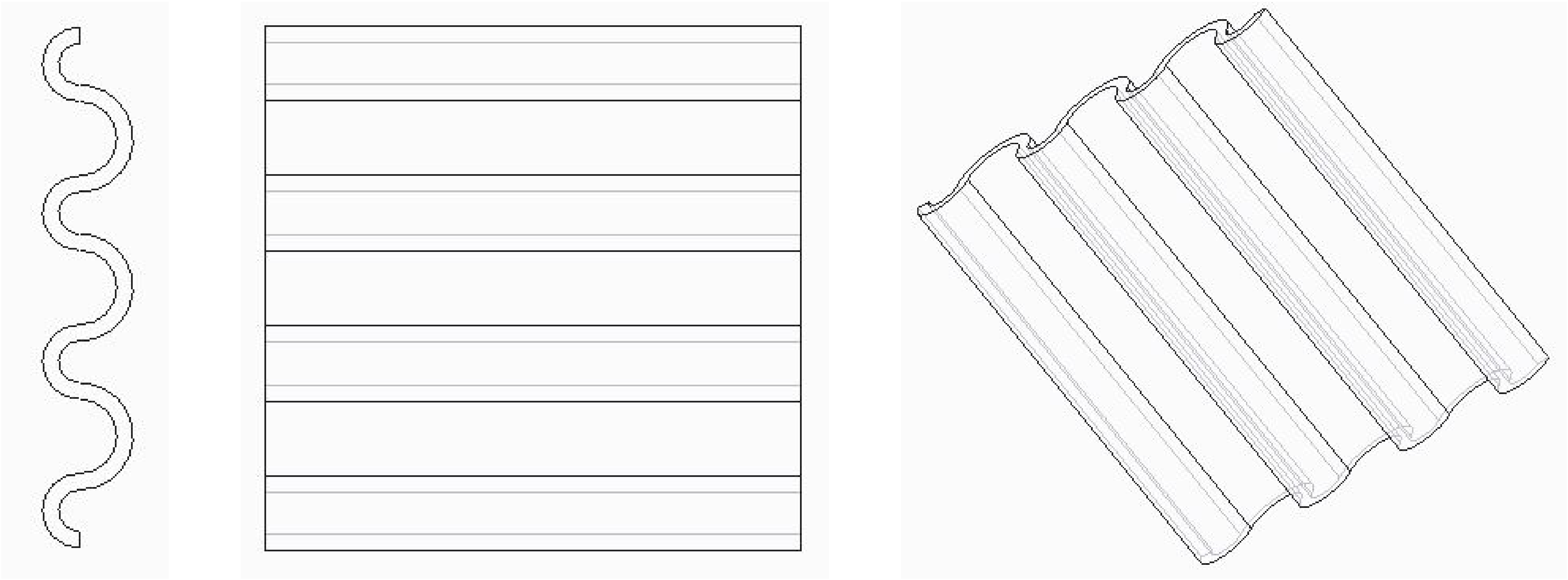


Fig D-4a,b,c. a) (Left) Profile view of conceptualized corrugated lamella, b) (Center) Front view of lamella, c) (Right) Default view of lamella.

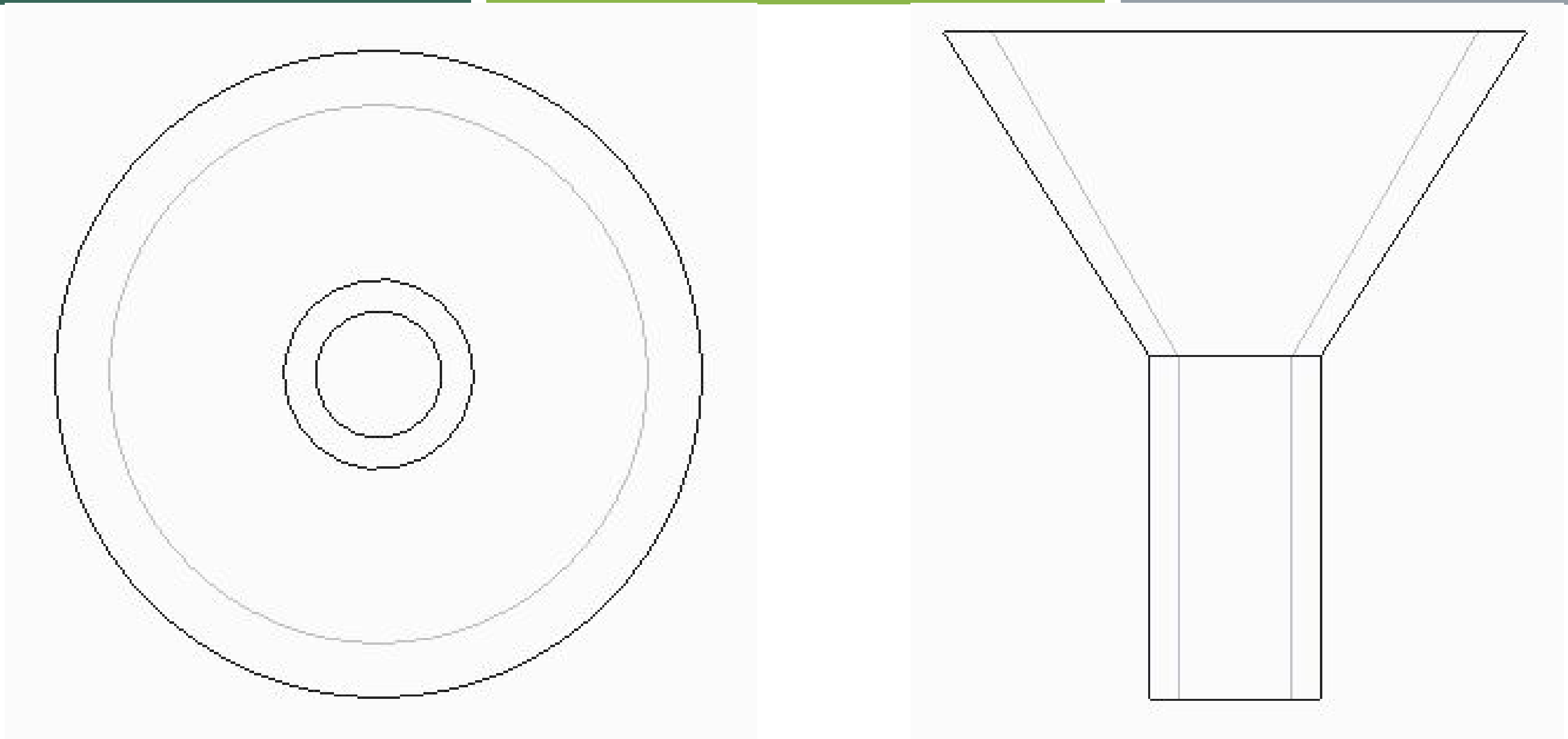


Fig D-5a,b. a. (Left) Top view of flexible extractor funnel, b. (Right) Profile view of funnel.

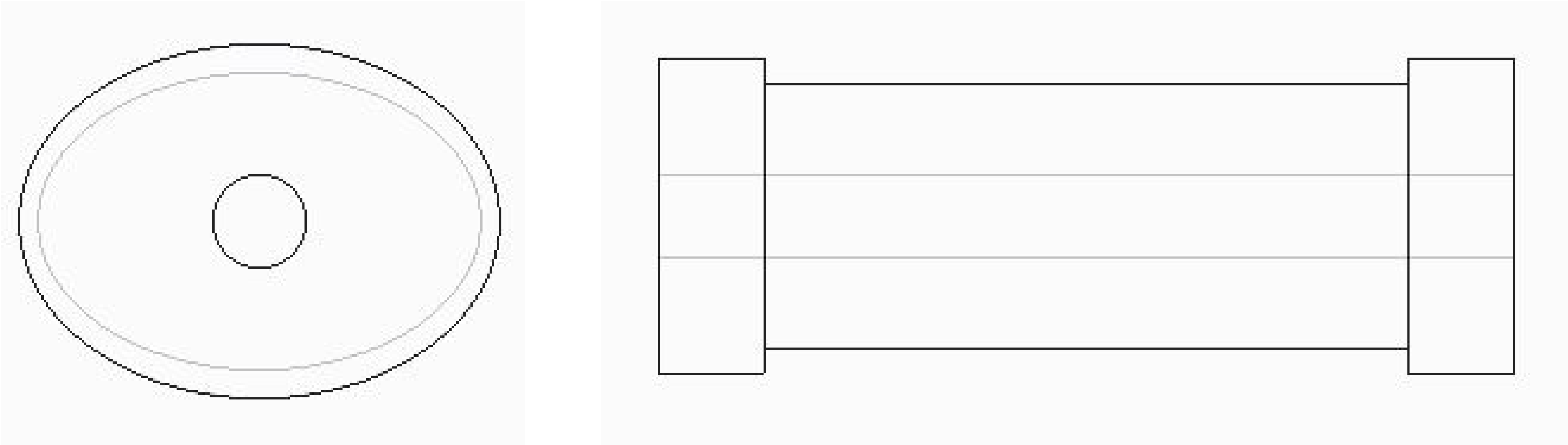


Fig 6 a,b. a) (Left) Profile View of concept cam to be used with extractor funnel, b) (Right) Longitudinal view of cam.