INTENSE PULSED LIGHT
FOR POWDERED FOOD PASTEURIZATION
WORKSHOP

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CFANS
COLLEGE OF FOOD, AGRICULTURAL AND NATURAL RESOURCE SCIENCES

INTENSE PULSED LIGHT
FOR FOOD SAFETY

System and process development and improvement

Outline

- Existing equipment and applications
- Engineering issues
- Design principles
- Individual components of a basic IPL system

Claranor: Pulsed Light Aseptic Packaging Systems

Dry and non-chemical solutions for inline packaging sterilization

Application to powdered foods

- IPL has been tested on a number of foods, including fruits, vegetables, meat, fish, honey, and powdered foods. For fruits, vegetables, meat, and fish, the objective of IPL treatment is mainly to reduce the initial microbial loads, and **it is difficult to reach complete pasteurization or sterilization using IPL without causing significant damages to quality due to the large size of these foods and limited penetration depth of IPL.** However, *higher degree of disinfection is highly feasible with powdered foods* as suggested by numerous reports in the scientific literature.

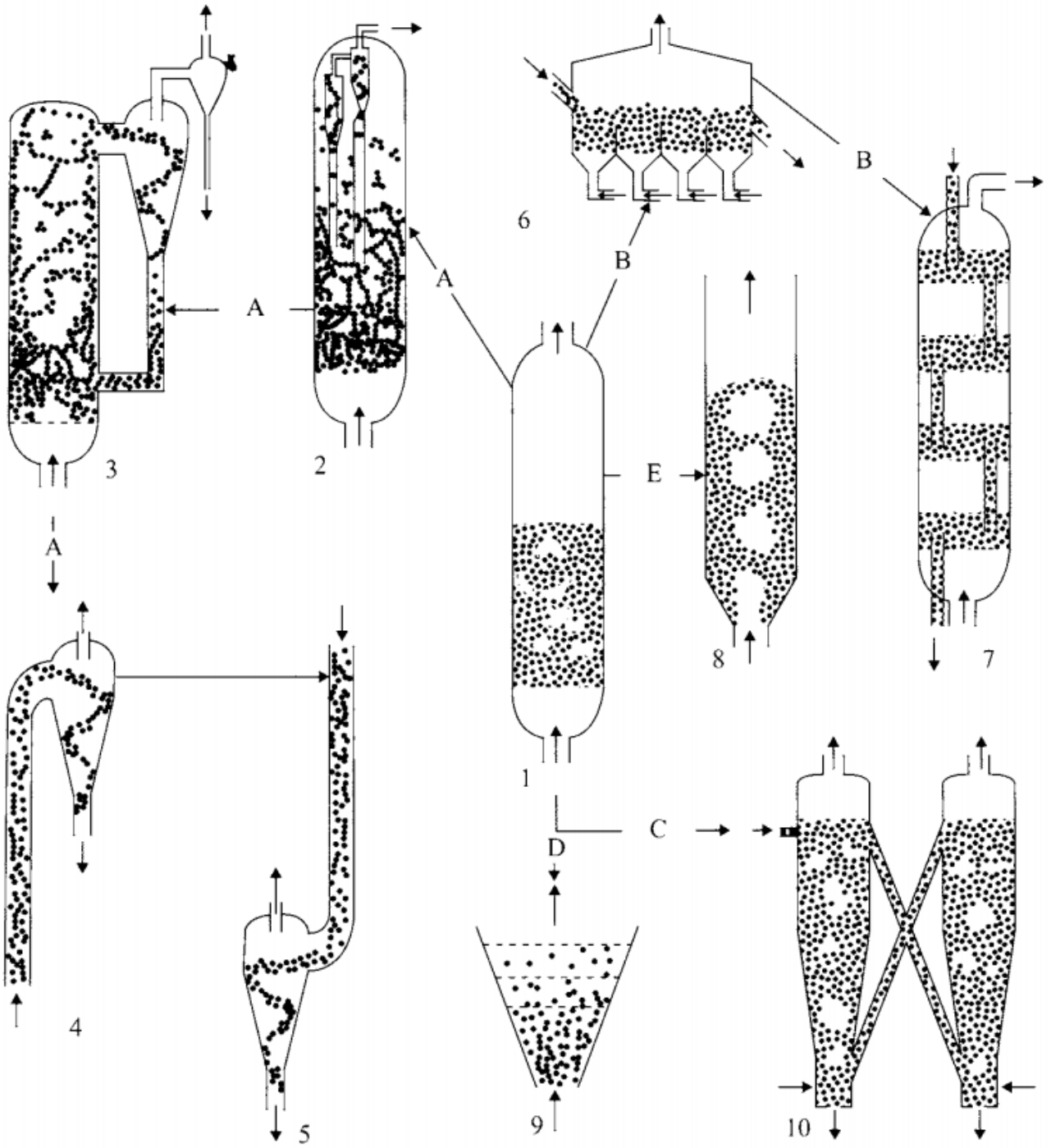
Key engineering problems to be solved for IPL treatment of powdered/particulate foods

- Continuous operation with reasonable throughput
- Sufficient exposure of particles to IPL
- Avoid significant physical or chemical properties changes, such as caking or drying
- Avoid overheating and minimize photo-oxidation of products

Our design principles

- It will be a continuous process
- Food particles are fluidized/suspended in treatment volume
- The aerodynamic conditions within the treatment volume will ensure all particles and their surfaces are exposed evenly to the prescribed IPL dosage (fluence) (sufficiently high probability)
- Energy input, flow rate, and treatment time can be conveniently regulated; and
- The temperature rise in products is kept under 60°C in order to maintain non-thermal claim.

Transport - continuous fluidization


A
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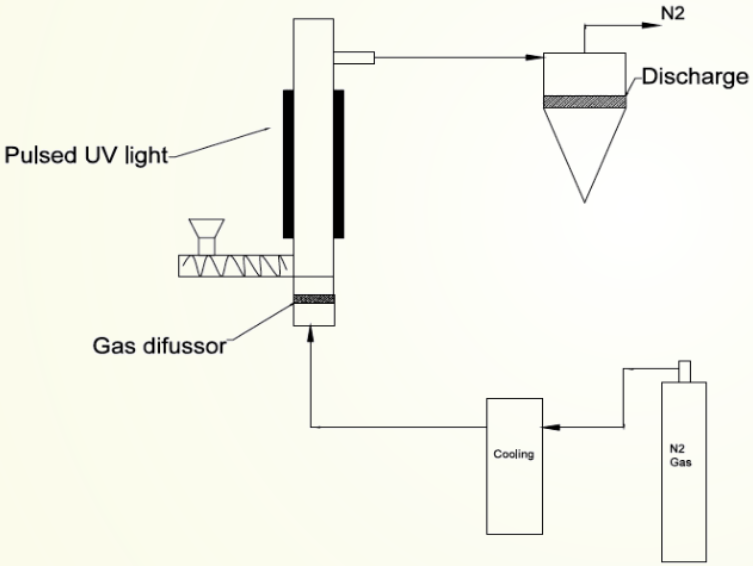
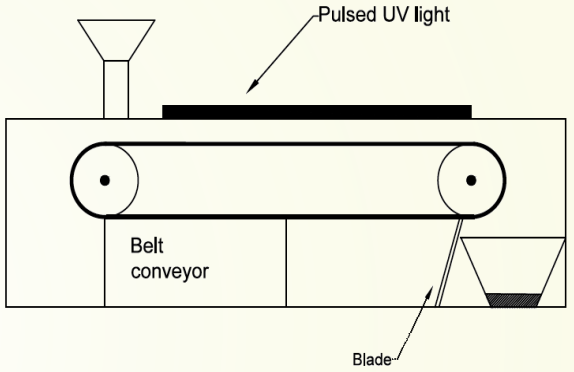
Reactor type
1: Bubbling fluidized bed reactor
2: Turbulent fluidized bed reactor
3: Circulating fluidized bed reactor
4: Riser reactor
5: Downer reactor
6: Cross-current fluidized bed reactor
7: Counter-current fluidized bed reactor
8: Spouted bed reactor
9: Floating fluidized bed reactor
10: Twin fluidized bed reactor

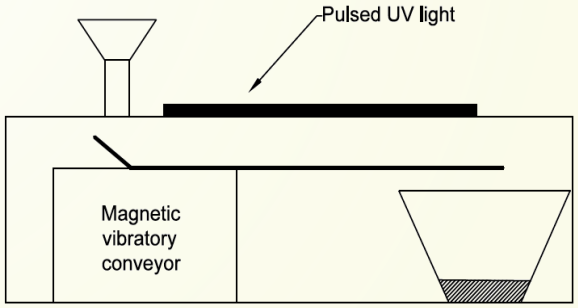
Key issues
A: Higher gas velocity
B: Counter-current contacting is beneficial
C: Incompatible differences in desired environment
D: Dusty environment
E: Large particles/low gas load


Oxidant
Ignition source
Explosion
Combustible dust
Dispersion of dust
Confinement of dust

Fluidization and transport mechanisms







Vertical fluidized bed and horizontal shaker/vibratory designs

Vibratory conveyer

- Feed rate adjustable
- 12"wide x 42" long x 3-1/2"tall open top tray.
- 304 stainless steel tray with off-end discharge of product.
- Sanitary II welds and 32Ra finish on interior product contact areas.
- Sanitary II welds with glass bead finish on exterior surfaces.
- Eliminating explosion hazards

Other consideration

- Transparent conveyer – top and bottom lights
- Reflective surface
  - Mirror
  - Highly polished stainless steel

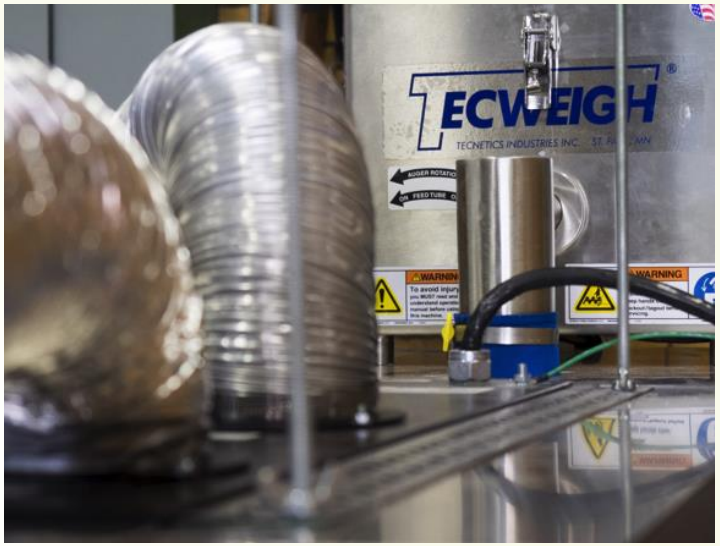
Volumetric feeder

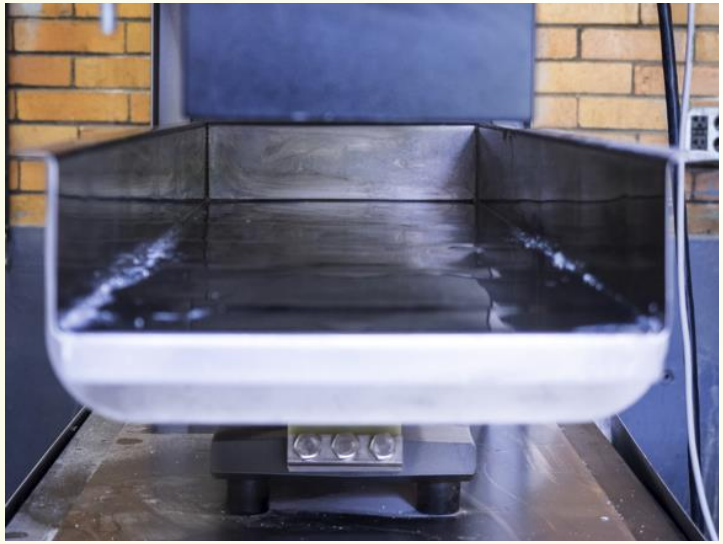
- Air-lock feeder with adjustable feed rates
- Automatic chain drive tensioner
- "Clear view" polycarbonate gear train panel – allows safe visual inspection of drive
- 304 stainless steel construction with sanitary Finish on Interior
- Uniform material pre-conditioning mixer

Pulsed light ensemble

- No harsh chemicals or mercury
- High irradiance: 1.27 J/cm^2 per pulse
- High peak power: >1.5 kW/cm^2
- Pulsed duration 360 µs
- Air cooled lamp enclosure
- Interchangeable lamps from UV-VIS-IR

Vibration bed pictures





Light source

- The type, power specification, and location of the light source
- Xenon lamp
- LED
- Pulse UV light
- Non-thermal plasma

Other components

- A control panel to regulate carrying gas (Nitrogen) and powder ratio, flow rates, pulsed light spectrum, frequency, and intensity, etc.
- Efficient and convenient cleaning

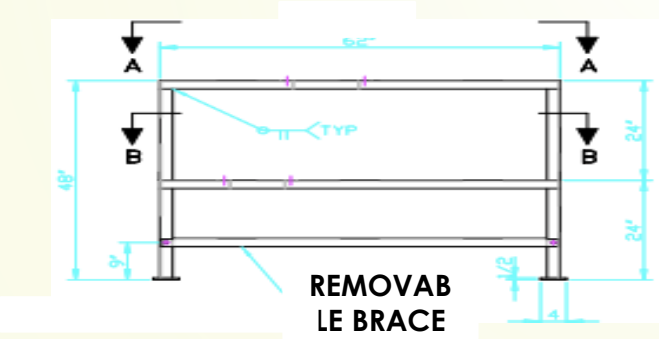
Critical process parameters

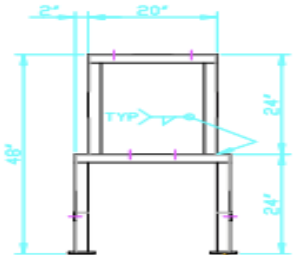
- number of pulses
- pulse intensity
- distance from the source of light
- residence time within the effective volume
- flow rate, and
- geometry and composition of particles

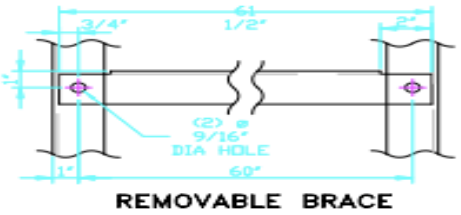
Fluence (Joule/meter^2 or J/m^2)

Structure

- Adjustable distance between the lamp and conveyor surface
- Food grade polycarbonate enclosure with removable front and rear panels
- Approximate dimension: 48'' tall x 24'' deep and 68'' long



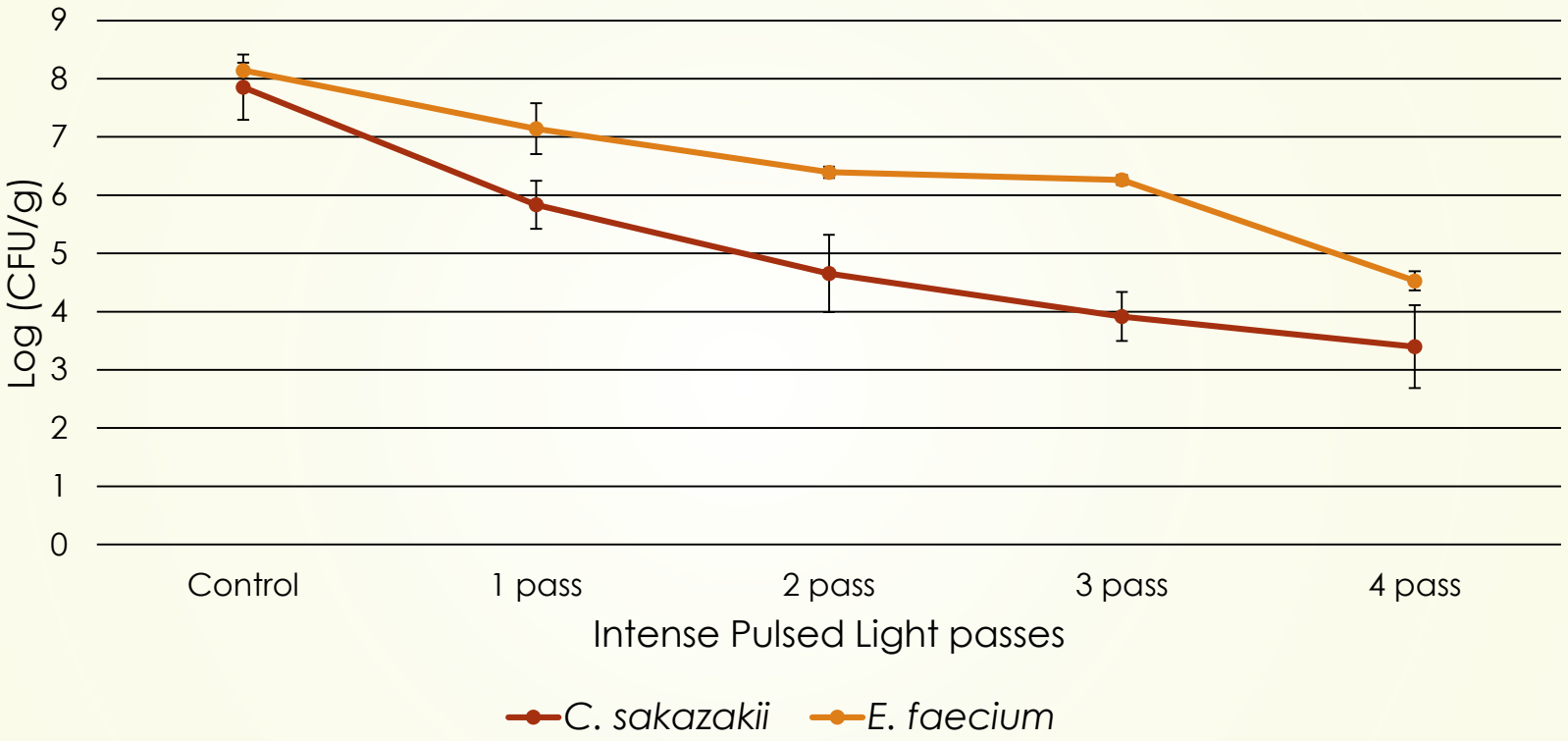




Inactivation of microbes inoculated on filter papers (unit: log CFU/g)

Treatment time (seconds)	*C. Sakazakii*	*E. Faecium*	*B. Cereus*
0	8.11	7.40	6.72
10	3.77	5.40	3.37
20	1.30	3.38	1.12
30	0	0	0

Log reductions of microbes inoculated on non-fat dry milk



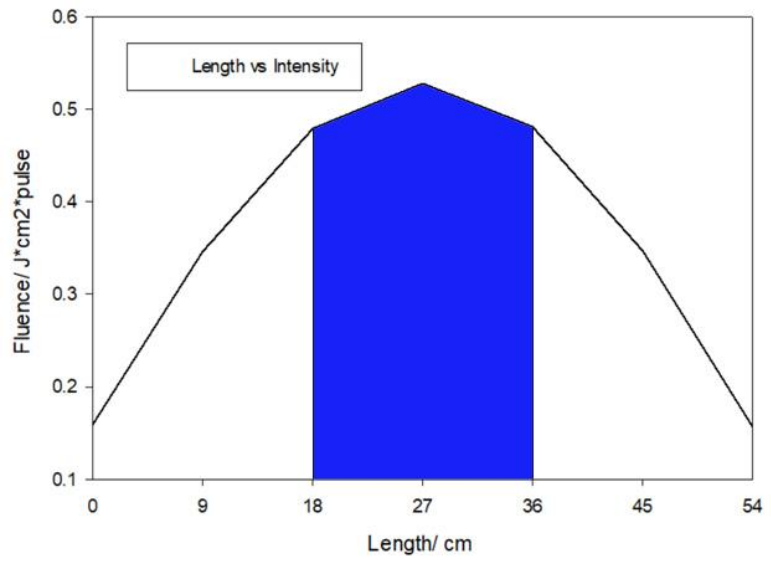
C. sakazakii (n=11), D-value of 23.09 seconds, and an average of 4.45 log reduction

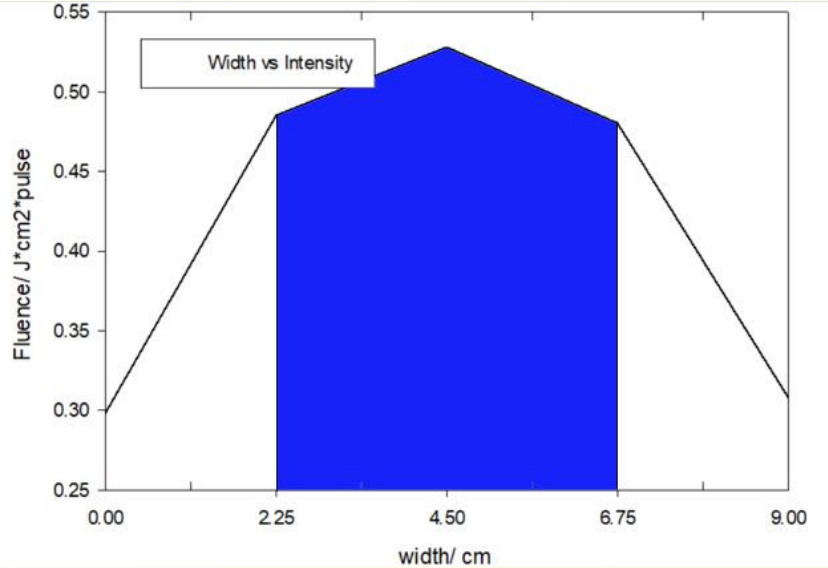
E. faecium (n= 3), D-value of 30.86 seconds, and an average of 3.61 log reduction

Key Issues with the lab scale IPL system

- The system was not capable of maintaining a stable sample temperature and water activity. Temperature rise and moisture loss/gain occur during treatment.
- We had to stop treatment before the temperature reaches 60 °C and equilibrate the sample to room temperature and desirable water activity level before next pass to avoid unnecessary quality changes due to higher temperature and to be able to achieve the necessary log reductions. This had to be repeated several times in order to reach 5 logs reduction.
- Although each pass was a continuous process, the treatment to achieve 5 logs reduction was a batch process.
- The pulse frequency and intensity of pulsed light might be too low to deliver energy required for a higher throughput.

IPL energy distribution and fluence received in process





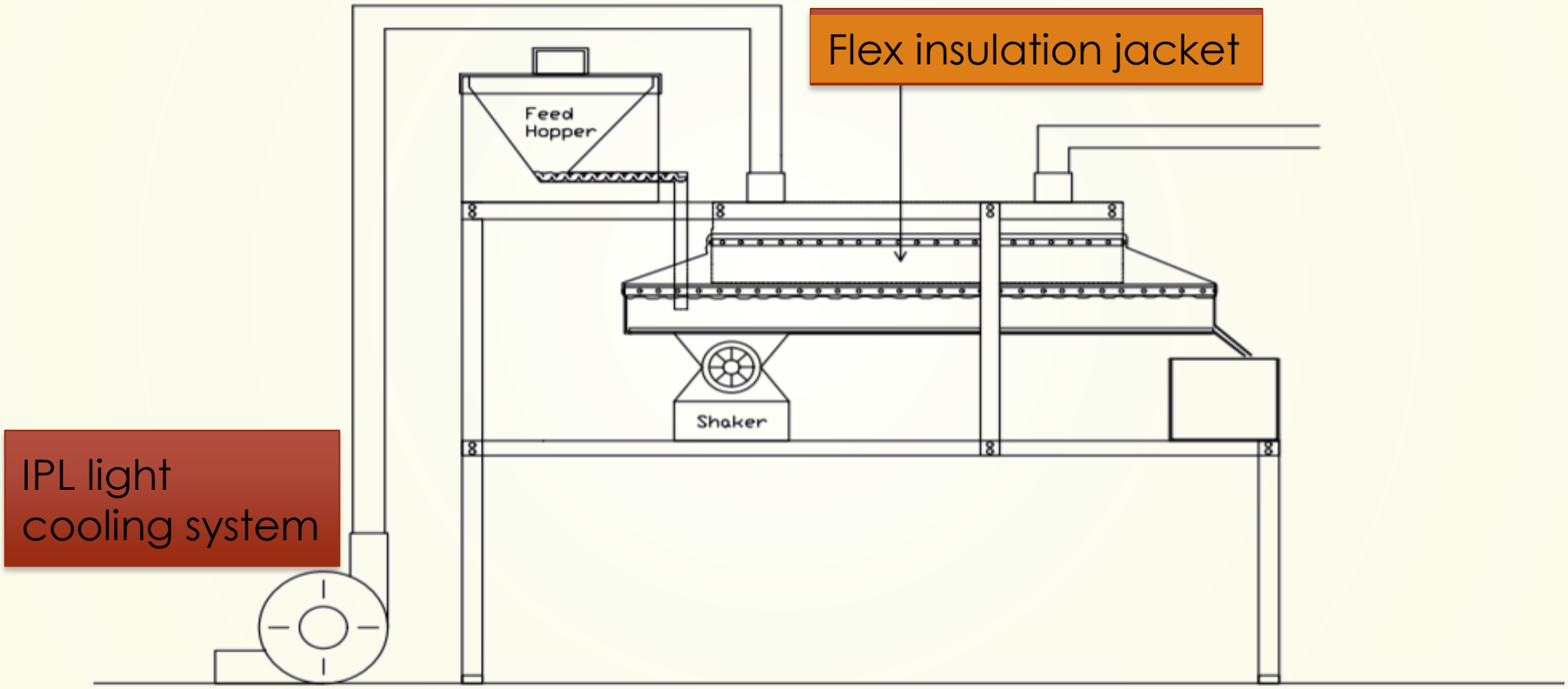
The IPL energy (J/cm^2/pulse) distribution on the vibrator surface. The highest influence area below the IPL lamp is marked in diagram with blue color.

Number of passes	1	2	3	4
Fluence(J/cm^{2*})	29.36	58.72	88.08	117.44

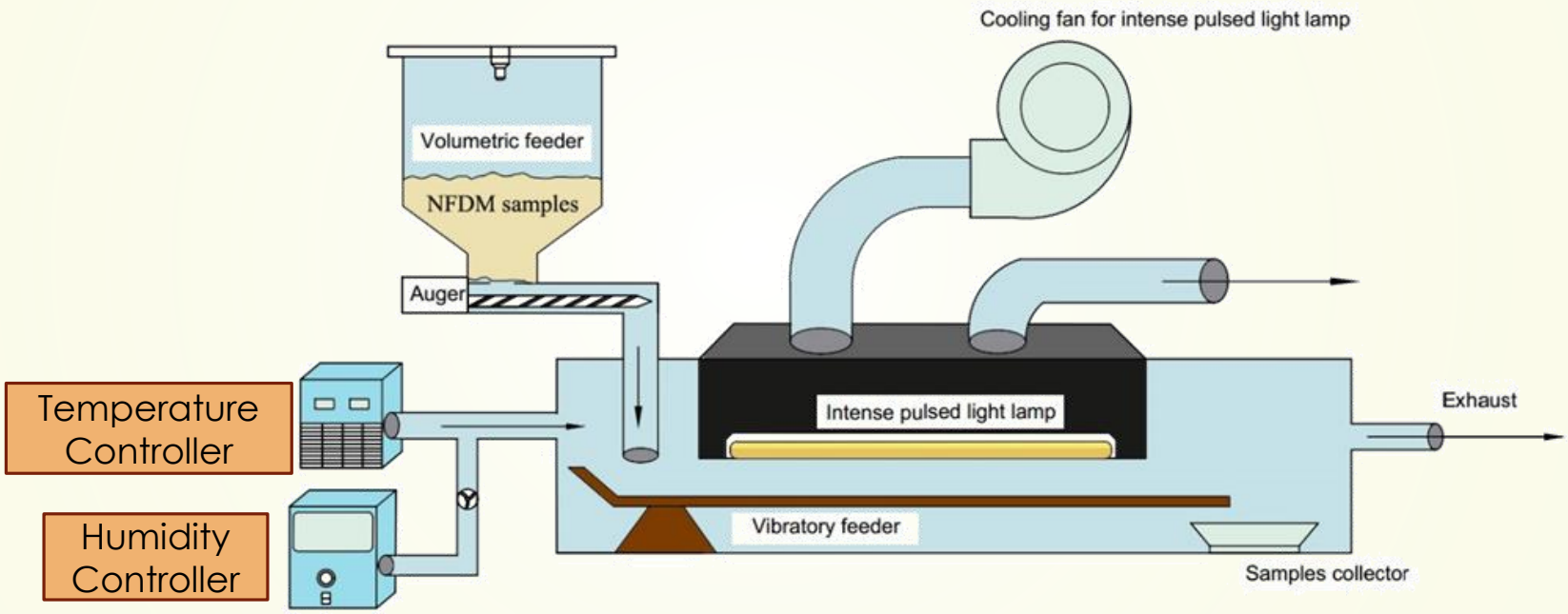
Design of the new pilot scale demonstration system

- The findings and experience described above are being used to develop the new pilot scale demonstration system that will have following features:
  - Pre-condition of food products
  - Accurate control of temperature and relative humidity
  - Continuous process
  - Potential higher pulse frequency and intensity light source
  - Higher throughput
  - Alternative light source such as single wavelength LED
  - Enhanced nutrition and quality preservation

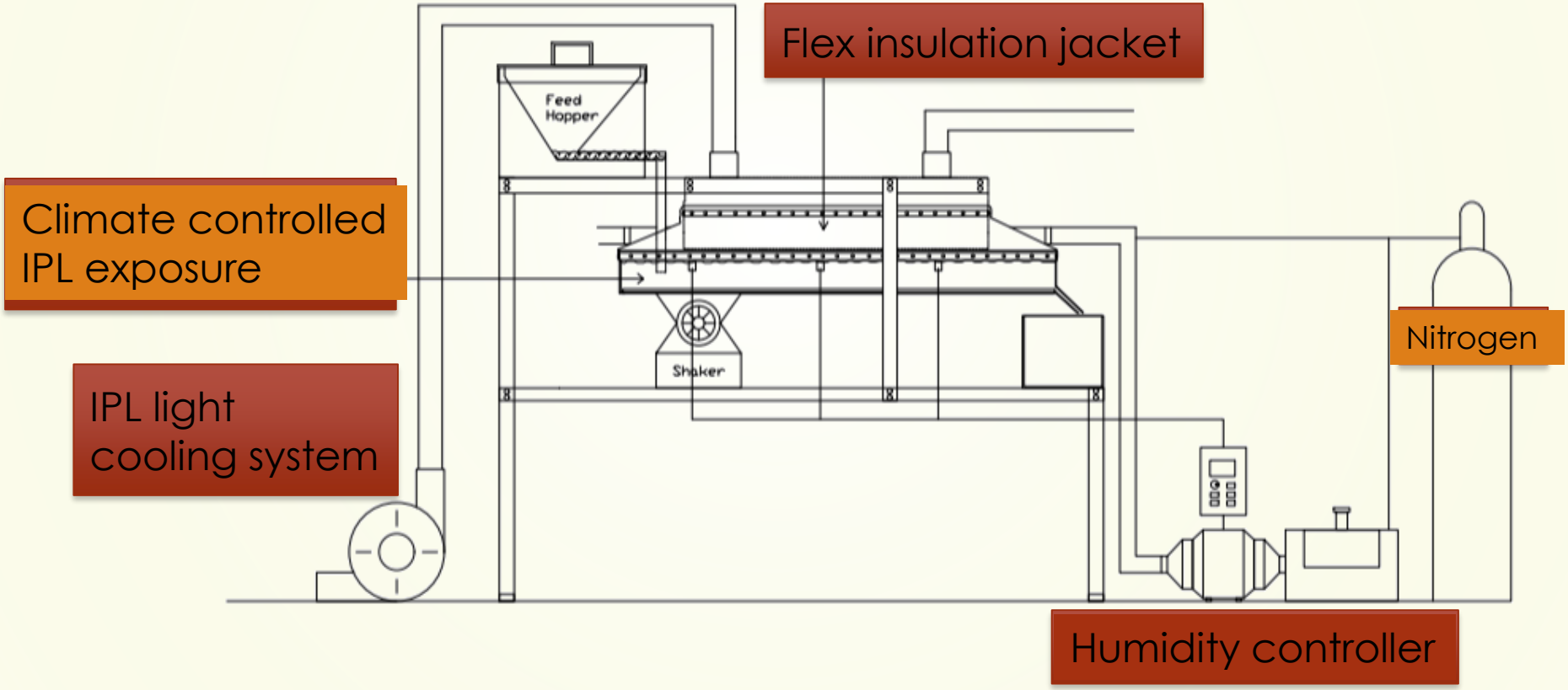
Closed system between shaker bed and IPL light



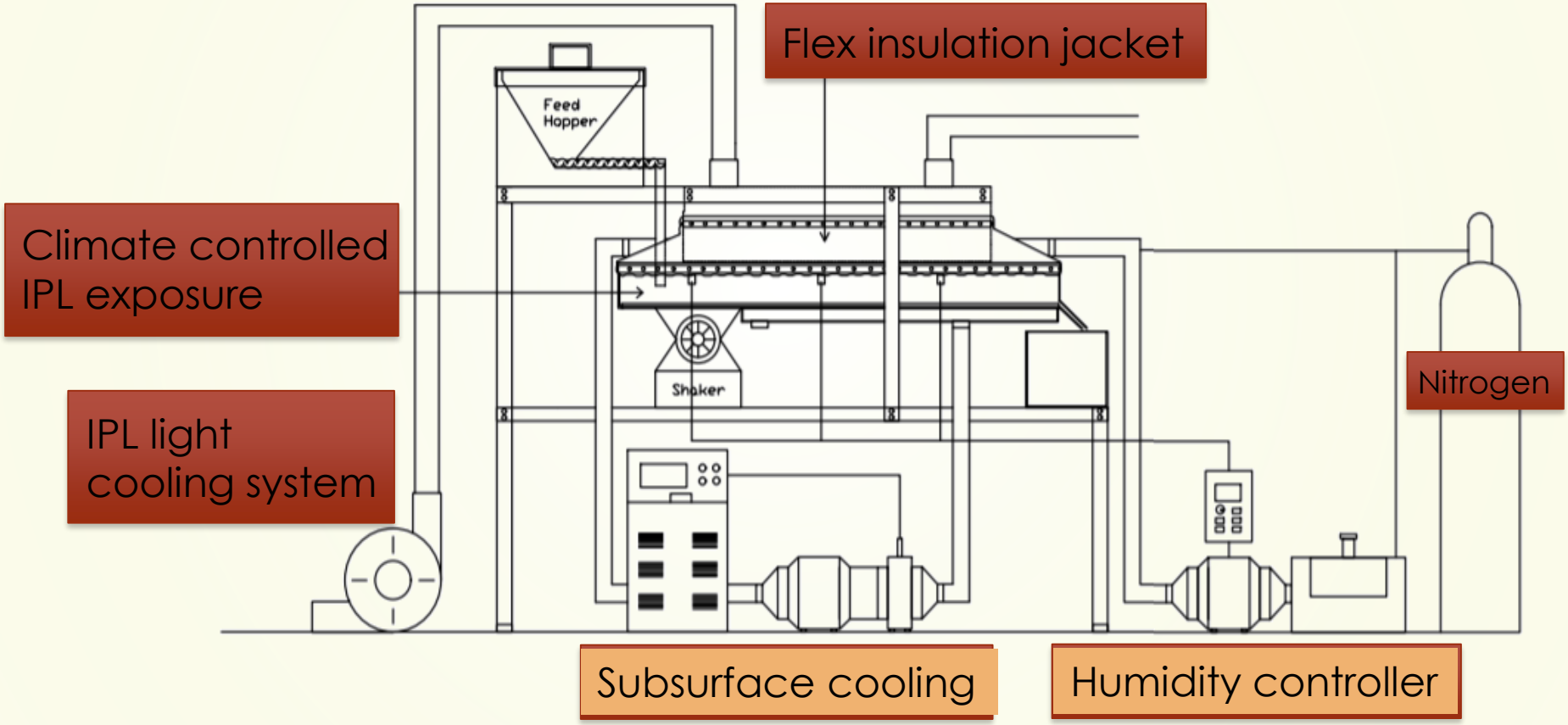
Temperature and humidity controller



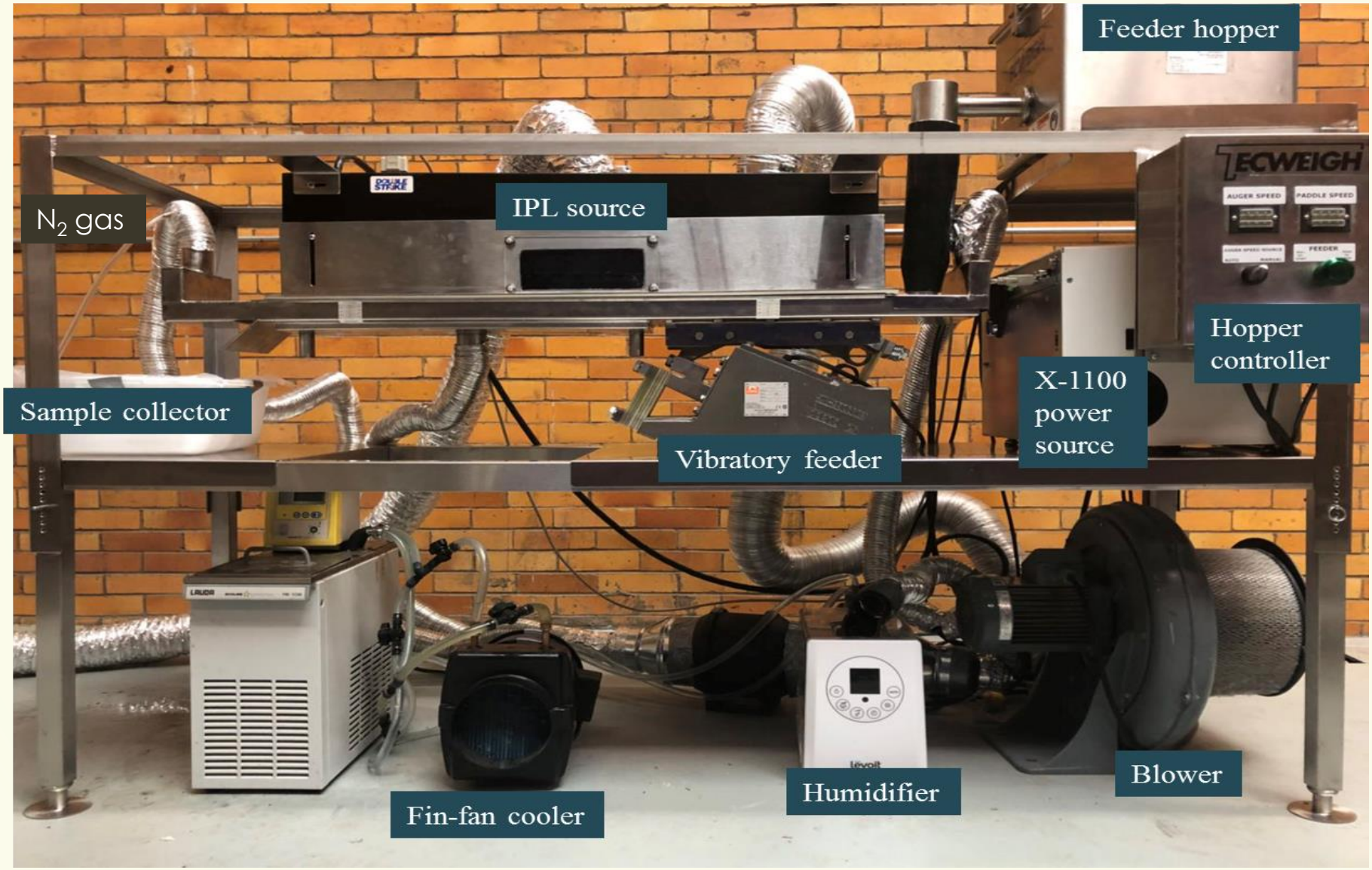
Climate control and nitrogen blanketing added



Subsurface cooling was added to extend substrate retention time



Picture of the new IPL prototype system

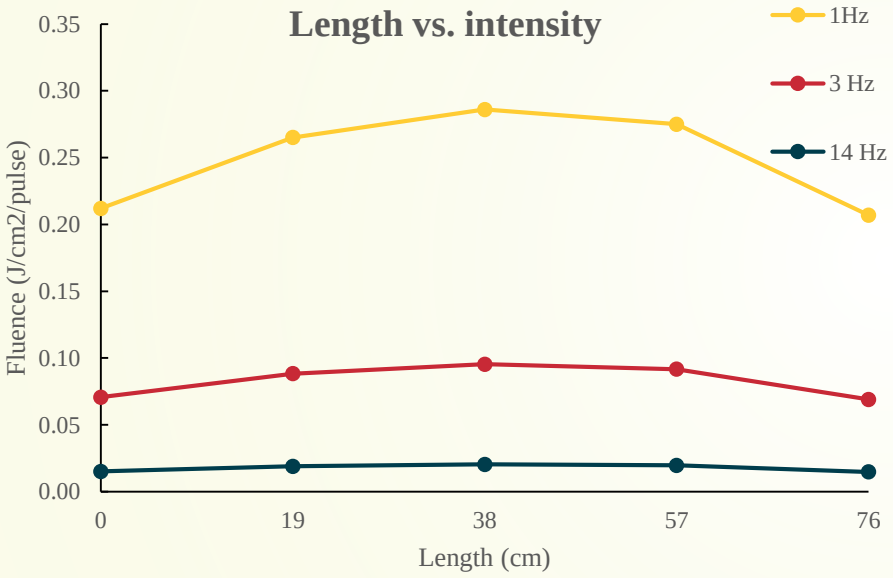


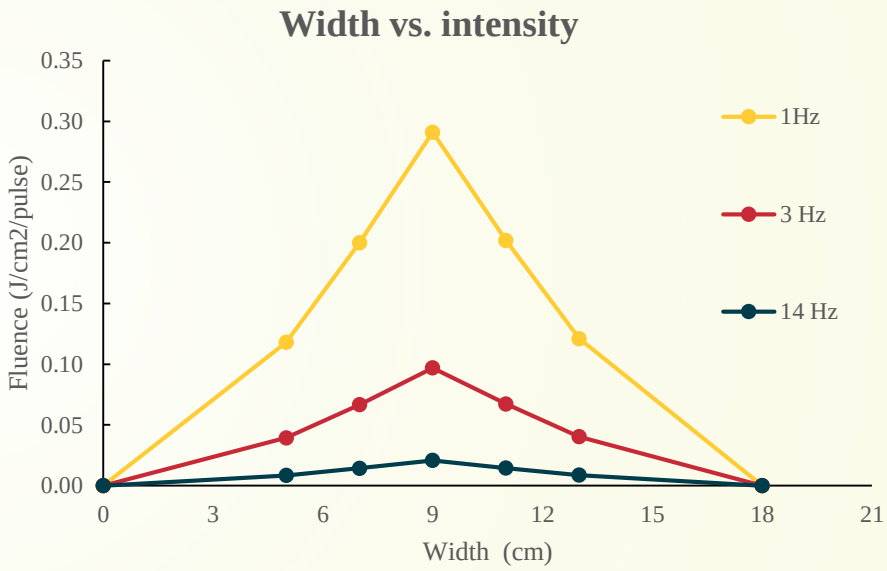
A new generation IPL system

This new IPL system has adjustable frequency, pulsed width, and peak fluence, which can be used to determine the most efficient parameters for microbes inactivation while causing minimal quality changes for powder samples.

Parameter	The original IPL lighting system	The new IPL lighting system
Lamp spectrum	190-1100 nm	190- 1100 nm
Voltage	3000 V	1000-3000 V
Pulse width	330 μs	100-7000 μs
Peak energy	830 J/pulse	37.5-2500 J/pulse
Pulse frequency	3 Hz	0.3-20 Hz
Lamp life	8760 hours	8760 hours
Max power to lamp	1516 J/sec	705 J/sec

IPL energy distribution and fluence received in process (X-1100 steripulse system)





The uniformity of IPL energy distribution, especially the length direction is improved significantly over the earlier IPL system

Treatment time (s)	30	60
Fluence(J/cm^{2*})	7.31	17.46

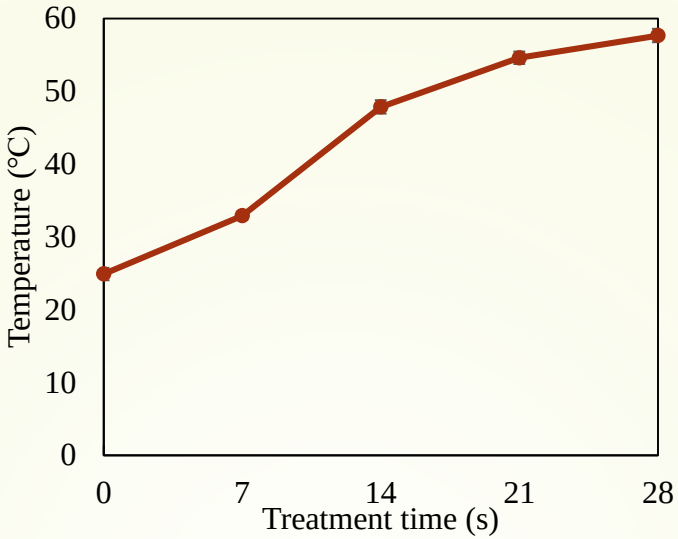
Log reductions of microbes inoculated on NFDM (log CFU/g)

Number of passes*	*C. Sakazakii* (log CFU/g)
0	0
1	2.02±0.43
2	3.19±0.69
3	3.93±0.42
4	4.45±0.71

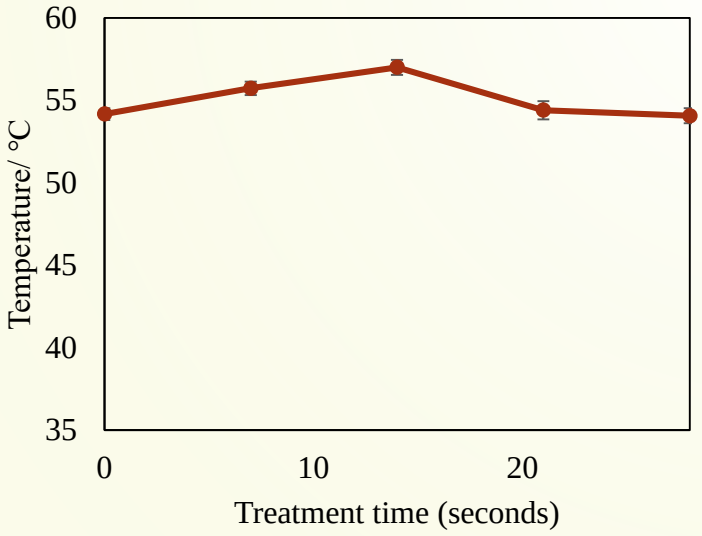
**28 seconds/pass using the original system*

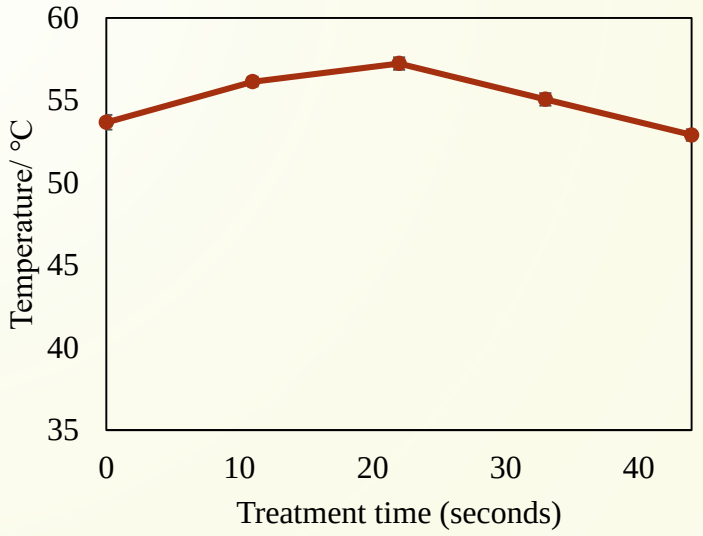
Treatment time (seconds)	*C. Sakazakii*** (log CFU/g)
0	0
28	3.96±0.05
44	5.44±0.17

**Improved results from the modified system



Temperature profiles of NFDM treated in the **original IPL system** after 28





Temperature profiles of NFDM treated in the **improved IPL system** for 28 and 44 s, respectively.

Particle size

The mean particle size of NFDM as a function of variable attributes

NFDM				
	Voltage (V)	**Feed rate (g/h)**	**Frequency (Hz)**	**Particle diameter (μm)**
Control	NA	NA	NA	**50.13±1.76a**
120s-UVC	NA	NA	NA	**52.41±0.68a**
1	3000	4200	1	**52.08±0.85a**
2	3000	4200	3	**51.41±1.92a**
3	3000	4200	14	**49.58±0.67a**
4	3000	8100	1	**48.52±2.03a**
5	3000	8100	3	**53.38±2.02a**
6	3000	8100	14	**51.27±0.98a**
7	2200	4200	1	**51.52±1.70a**
8	2200	4200	3	**51.79±0.59a**
9	2200	4200	14	**51.71±1.32a**
10	2200	8100	1	**51.63±0.73a**
11	2200	8100	3	**51.15±0.89a**
12	2200	8100	14	**50.30±1.75a**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$). No caking appeared after IPL treatment.

Particle size

The mean particle size wheat flour as a function of variable attributes

Wheat flour				
	Voltage (V)	Feed rate (g/h)	Frequency (Hz)	Particle diameter (μm)
Control	NA	NA	NA	**54.19±0.99a**
120s-UVC	NA	NA	NA	**55.34±0.89a**
13	3000	3600	1	**54.94±1.32a**
14	3000	3600	3	**52.95±0.71a**
15	3000	3600	14	**54.70±0.35a**
16	3000	7200	1	**53.53±1.51a**
17	3000	7200	3	**55.39±1.20a**
18	3000	7200	14	**55.46±1.50a**
19	2200	3600	1	**51.83±3.20a**
20	2200	3600	3	**52.41±1.53a**
21	2200	3600	14	**53.18±2.20a**
22	2200	7200	1	**55.47±1.21a**
23	2200	7200	3	**52.88±1.89a**
24	2200	7200	14	**53.62±1.78a**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$). No caking appeared after IPL treatment.

Temperature and water activity profiles of **NFDM** during the new IPL treatment

The relative humidity (RH) in IPL chamber was maintained at **25-30%** during the IPL treatment

	Initial temperature± SD (°C)	Final temperature± SD (°C)	Initial water activity level± SD	Final water activity level± SD
NFDM				
120s-UVC	55.2±1.0A	**56.3±0.8B**	0.25±0.01C	**0.24±0.01E**
1	55.9±0.6A	**56.2±0.6B**	0.26±0.01C	**0.25±0.01E**
2	55.2±0.3A	**56.7±0.6B**	0.25±0.01C	**0.25±0.01E**
3	55.9±0.6A	**56.2±0.6B**	0.26±0.01C	**0.26±0.01E**
4	56.1±0.6A	**56.9±0.6B**	0.27±0.02C	**0.26±0.01E**
5	55.2±0.9A	**56.4±0.8B**	0.24±0.01C	**0.24±0.01E**
6	54.9±0.9A	**55.7±1.2B**	0.25±0.02C	**0.25±0.01E**
7	55.9±0.8A	**56.3±0.5B**	0.26±0.02C	**0.25±0.01E**
8	55.2±0.3A	**56.5±0.9B**	0.24±0.01C	**0.24±0.01E**
9	55.9±0.6A	**56.1±0.8B**	0.25±0.01C	**0.25±0.01E**
10	55.4±0.3A	**56.5±0.5B**	0.24±0.02C	**0.24±0.01E**
11	55.5±0.3A	**56.5±0.9B**	0.24±0.01C	**0.24±0.01E**
12	55.9±0.6A	**57.2±0.5B**	0.25±0.01C	**0.24±0.01E**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$).

Temperature and water activity profiles of **wheat flour** during the new IPL treatment

The RH in IPL chamber was maintained at **35-40%** during the IPL treatment

	Initial temperature± SD (°C)	Final temperature± SD (°C)	Initial water activity level± SD	Final water activity level± SD
Wheat flour				
120s-UVC	54.2±0.8A	**56.9±1.1B**	0.40±0.01D	**0.35±0.01F**
1	54.9±0.6A	**56.8±0.6B**	0.40±0.01D	**0.36±0.01F**
2	54.2±0.6A	**56.9±0.9B**	0.40±0.01D	**0.37±0.01F**
3	54.9±0.6A	**56.2±1.1B**	0.39±0.01D	**0.35±0.01F**
4	54.1±0.6A	**56.9±0.6B**	0.41±0.02D	**0.35±0.01F**
5	54.2±0.9A	**56.6±0.8B**	0.39±0.01D	**0.36±0.01F**
6	54.4±0.8A	**56.7±0.9B**	0.40±0.01D	**0.36±0.01F**
7	54.5±0.8A	**56.3±0.5B**	0.40±0.01D	**0.35±0.01F**
8	54.5±0.3A	**56.5±0.8B**	0.39±0.01D	**0.37±0.01F**
9	53.9±0.9A	**56.5±1.3B**	0.41±0.01D	**0.35±0.01F**
10	54.6±0.9A	**56.6±0.9B**	0.41±0.01D	**0.36±0.01F**
11	54.7±0.6A	**56.3±0.8B**	0.41±0.01D	**0.36±0.01F**
12	54.7±0.6A	**56.1±0.5B**	0.41±0.02D	**0.35±0.01F**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$)

Color change

Color difference (ΔE) of **NFDM** after new IPL treatment

NFDM				
	Voltage (V)	**Feed rate (g/h)**	**Frequency (Hz)**	**ΔE**
120s-UVC	NA	NA	NA	**3.36±0.28a**
1	3000	4200	1	**2.49±0.12b**
2	3000	4200	3	**2.17±0.16c**
3	3000	4200	14	**1.94±0.03d**
4	3000	8100	1	**2.12±0.08c**
5	3000	8100	3	**1.99±0.22cd**
6	3000	8100	14	**1.79±0.29cd**
7	2200	4200	1	**2.27±0.23bc**
8	2200	4200	3	**2.02±0.29cd**
9	2200	4200	14	**1.82±0.09d**
10	2200	8100	1	**2.09±0.16cd**
11	2200	8100	3	**1.75±0.15e**
12	2200	8100	14	**1.58±0.07e**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$). Color change for IPL treated NFDM was less than that of UVC treatment.

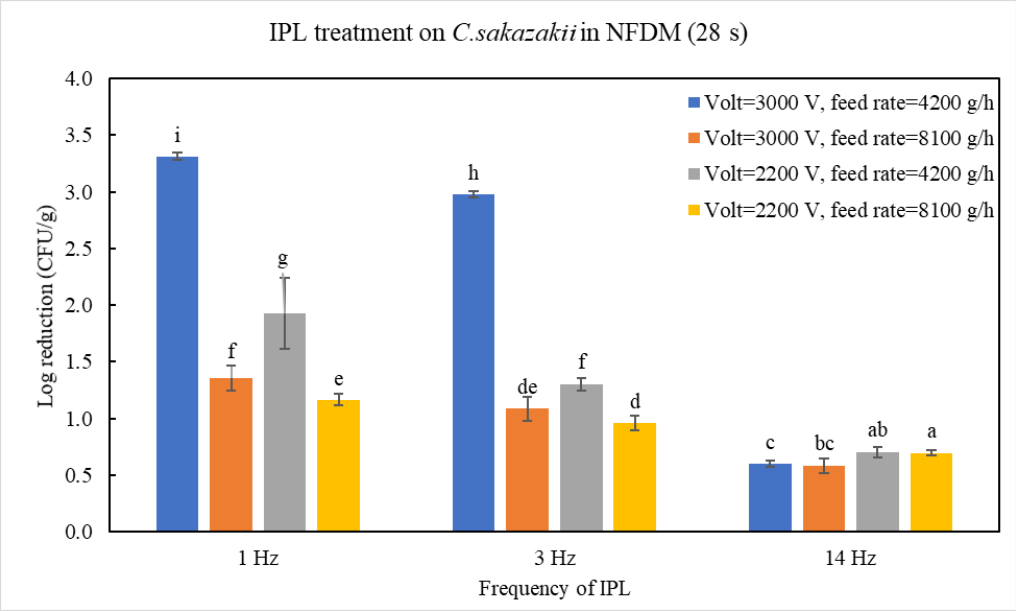
Color change

Color difference (ΔE) of **wheat flour** after new IPL treatment

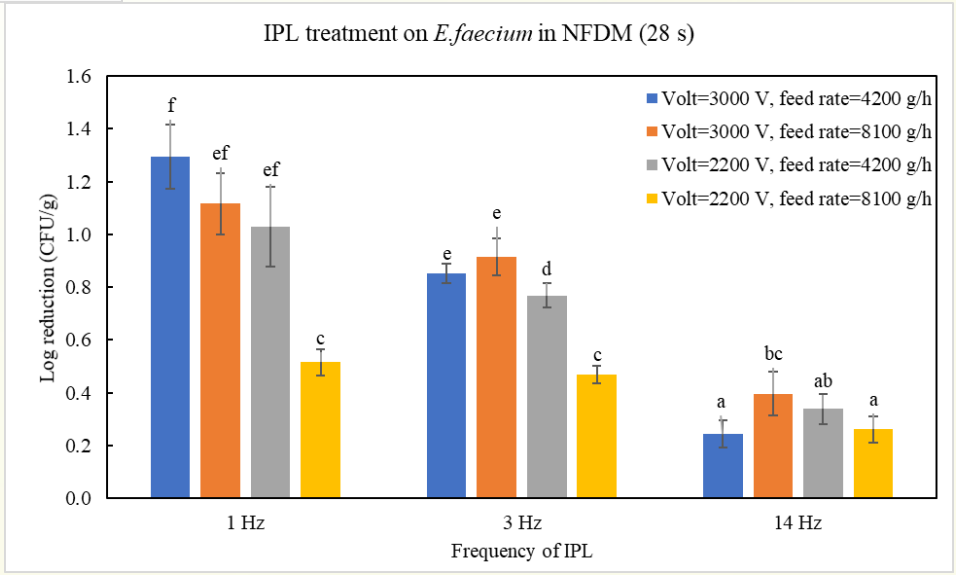
Wheat flour				
	Voltage (V)	**Feed rate (g/h)**	**Frequency (Hz)**	**ΔE**
120s-UVC	NA	NA	NA	**0.66±0.22a**
13	3000	3600	1	**0.23±0.15b**
14	3000	3600	3	**0.20±0.11b**
15	3000	3600	14	**0.22±0.14b**
16	3000	7200	1	**0.11±0.10b**
17	3000	7200	3	**0.10±0.06b**
18	3000	7200	14	**0.16±0.14b**
19	2200	3600	1	**0.19±0.06b**
20	2200	3600	3	**0.16±0.06b**
21	2200	3600	14	**0.10±0.08b**
22	2200	7200	1	**0.21±0.10b**
23	2200	7200	3	**0.21±0.05b**
24	2200	7200	14	**0.11±0.06b**

Data in the same column followed by the same uppercase letter are not significantly different ($P > 0.05$). No noticeable color change for IPL treated wheat flour ($\Delta E<0.5$).

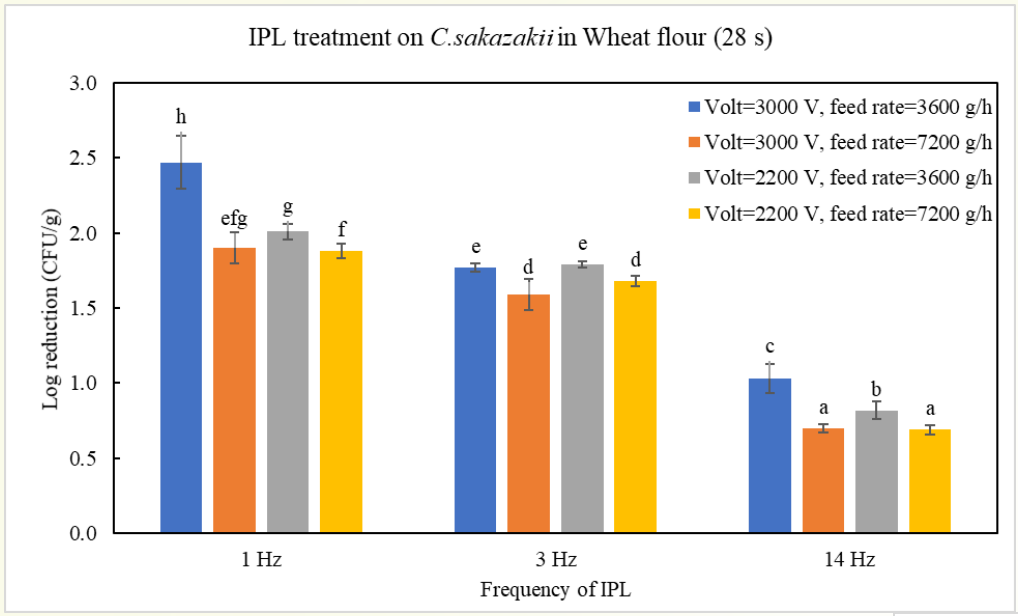
Effect of new IPL process parameters (**Frequency, voltage and feed rate**) on microorganisms in **NFDM**



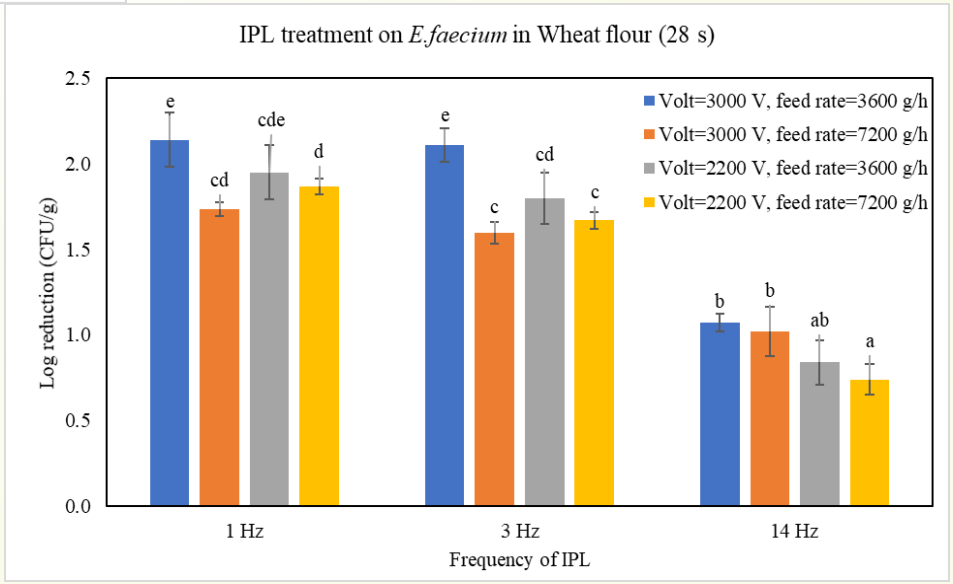
The total fluence (energy flux) of each treatment is 7.13 J/cm^2 (28 s), the feed rate of NFDM at 4200 and 8100 g/h were associated with layer thickness of ~1.2 and 2.0 mm, respectively.



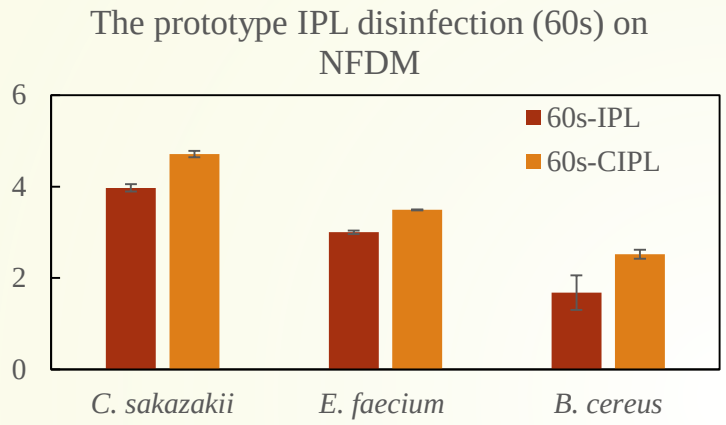
Effect of new IPL process parameters (**Frequency, voltage and feed rate**) on microorganisms in **wheat flour**

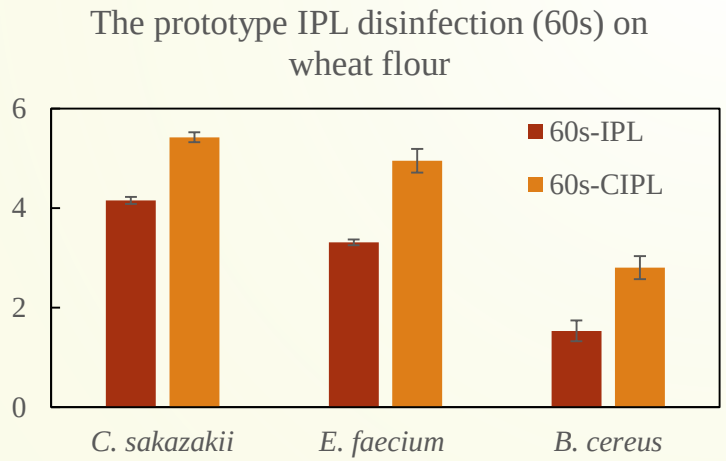


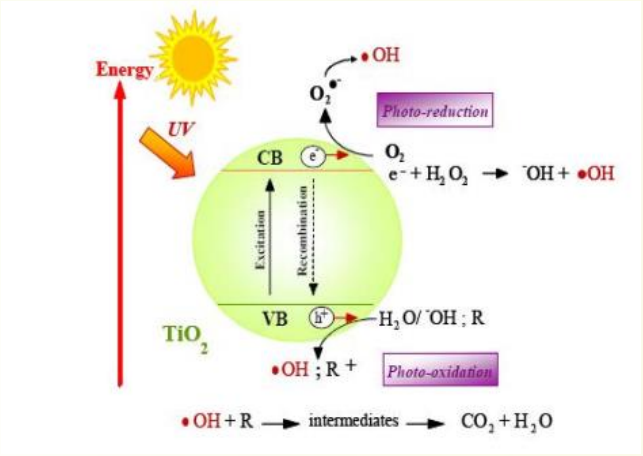
The total fluence (energy flux) of each treatment is 7.13 J/cm^2 (28 s), the feed rate of NFDM at 4200 and 8100 g/h were associated with layer thickness of ~1.2 and 2.0 mm, respectively.



Synergistic effects of IPL and titanium dioxide photocatalyst



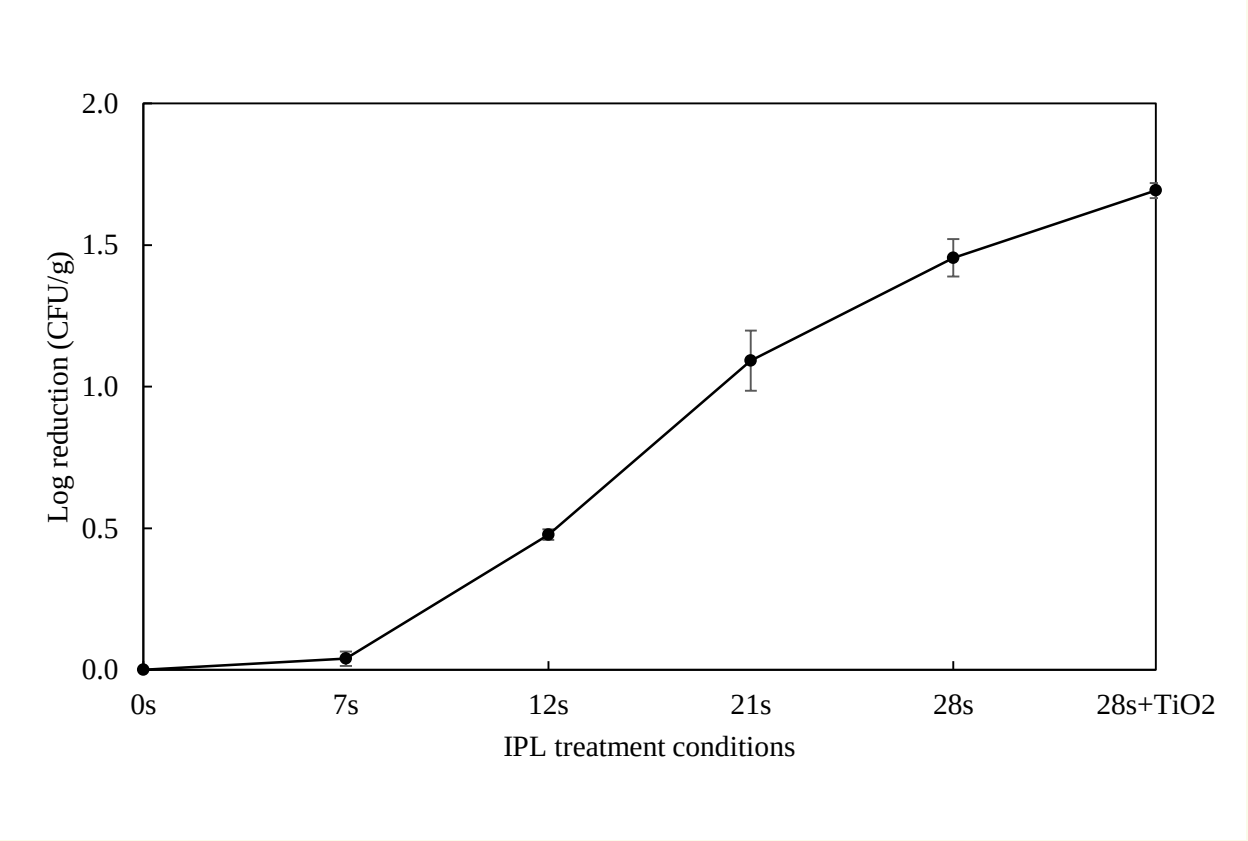




- **Additional one $\log_{10}$ CFU/g reduction was obtained in both powdered foods when TiO_2 is combined with IPL for all types of bacteria or spores.**

Evaluation of synergistic effects of IPL and titanium dioxide (cIPL)

Effect of IPL or IPL+TiO_2 beads (2 mm) on inactivating *B. cereus* inoculated in **mesquite flour**. The total fluence (energy flux) of 60s-IPL treatment is 17.46 J/cm^2.



The disinfection of seeds using cIPL treatment

Disinfection of different **seeds** with **IPL or cIPL** treatments

Type of microorganism and treatment conditions	Type of seed				
	Wheat	Sunflower seed	Almond	Rice grain	Peanut
C. sakazakii (IPL)	4.21 logs (120s)	3.78 logs (60s)	2.69 logs (60s)	0.71 logs (40s)	1.18 logs (40s)
C. sakazakii (IPL+TiO_2)	5.00 logs (120s)	4.71 logs (60s)	2.90 logs (60s)		
E. faecium (IPL)	4.16 logs (120s)	1.93 logs (40s)	1.42 logs (40s)	1.31 logs (40s)	0.70 logs (40s)
B. cereus (IPL)	0.81 logs (60s)	1.05 logs (40s)	0.97 logs (40s)	0.48 logs (40s)	0.55 logs (40s)
Natural microorganism (IPL+TiO_2)	1.4 logs (120s)				

Energy consumption for the cIPL disinfection of seeds

IPL energy (D_{10}) required to achieve 90% reduction of microbes on different **seeds**.

Type of microorganism and treatment conditions	Type of seeds				
	Wheat	Sunflower seed	Almond	Rice grain	Peanut
C. sakazakii (IPL)	37.3 J/g	27.6 J/g	9.9 J/g	77.2 J/g	17.3 J/g
C. sakazakii (IPL+TiO_2)	31.4 J/g	22.1 J/g	9.2 J/g		
E. faecium (IPL)	37.7 J/g	36 J/g	12.6 J/g	41.8 J/g	25.5 J/g
B. cereus (IPL)	96.8 J/g	66.2 J/g	18.4 J/g	114.2 J/g	32.4 J/g
Natural microorganism (IPL+TiO_2)	112.0 J/g				

Energy consumption for the IPL disinfection of powders

IPL energy (D_{10}) required to achieve 90% reduction of microbes on different **powders**.

Type of microorganism and treatment conditions	Type of powdered foods		
	NFDM	Wheat flour	Mesquite flour
C. sakazakii (IPL)	45.5 J/g	50.1 J/g	
C. sakazakii (IPL+TiO_2)	38.7 J/g	38.4 J/g	
E. faecium (IPL)	60.6 J/g	62.8 J/g	
E. faecium (IPL+TiO_2)	52.3 J/g	42.0 J/g	
B. cereus (IPL)	107.0 J/g	135.9 J/g	167.2 J/g
B. cereus (IPL+TiO_2)	72.8 J/g	74.5 J/g	143.5 J/g

A comparison of four non-thermal technologies

Technology	The highest disinfection capability for one pass	Advantages	Disadvantages
IPL	5.42 $\log_{10}$ CFU/g of C. sakazakii	(1) Excellent disinfection achieved when combing with TiO_2 photocatalysts. (2) More accurate environment control (3) Higher throughput (~8000 g/hrs) (4) Minimal or slight quality loss (5) No caking or burning (6) Less safety concerns	(1) Photo-oxidation may be induced after extended IPL treatment
Non-thermal Plasma (plasma Jet)	3.27 $\log_{10}$ CFU/g of C. sakazakii	(1) Relatively high $\log_{10}$ CFU/g reduction. (1) Minimal quality loss (2) No caking or burning (3) No direct contact between samples and electrodes	(1) Less log reduction (2) More difficult to control (3) Pneumatic transportation (4) Higher energy consumption (5) Oxidation
Gamma irradiation	3.51 $\log_{10}$ CFU/g of B. cereus spore	(1) Efficient in microbial inactivation especially for bacterial spore inactivation (2) No caking or burning (3) No significant change in some sensitive nutrient profiles below the standard dose limitation (10 kGy).	(1) More research regarding safety issues and quality profiles of products need to be investigated when utilizing higher gamma dose (> 10kGy). (2) Oxidation
UV light	2.14 $\log_{10}$ CFU/g of C. sakazakii	(1) UV device is cheaper and easier to be accessed	(1) Lower $\log_{10}$ CFU/g reduction because of limited penetration (2) Relatively high photo-oxidation induced (3) Lower throughput (4) Relatively higher quality loss

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Thank you!

Questions?

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