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Waste Utilization for Biohydrogen Production Through Photobiological Methods

(Review Study)

Melitos George, Voulkopoulos M Xenofon, Zabaniotou Anastasia

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Presentation Contents

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Hydrogen (1)

- H_2 - The most common chemical element in the universe
- High heating value - High efficiency
- Carbon Free Fuel - Zero GHGs emissions
- Alternative solution in environmental problems

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Hydrogen (2)

Electrochemical

- Electrolysis
- Photo-electrolysis
- High Temperature Electrolysis

Biochemical

- Dark fermentation
- Photo fermentation
- Biophotolysis

Thermochemical

- Gasification
- Steam Methane Reforming
- Partial Oxidation

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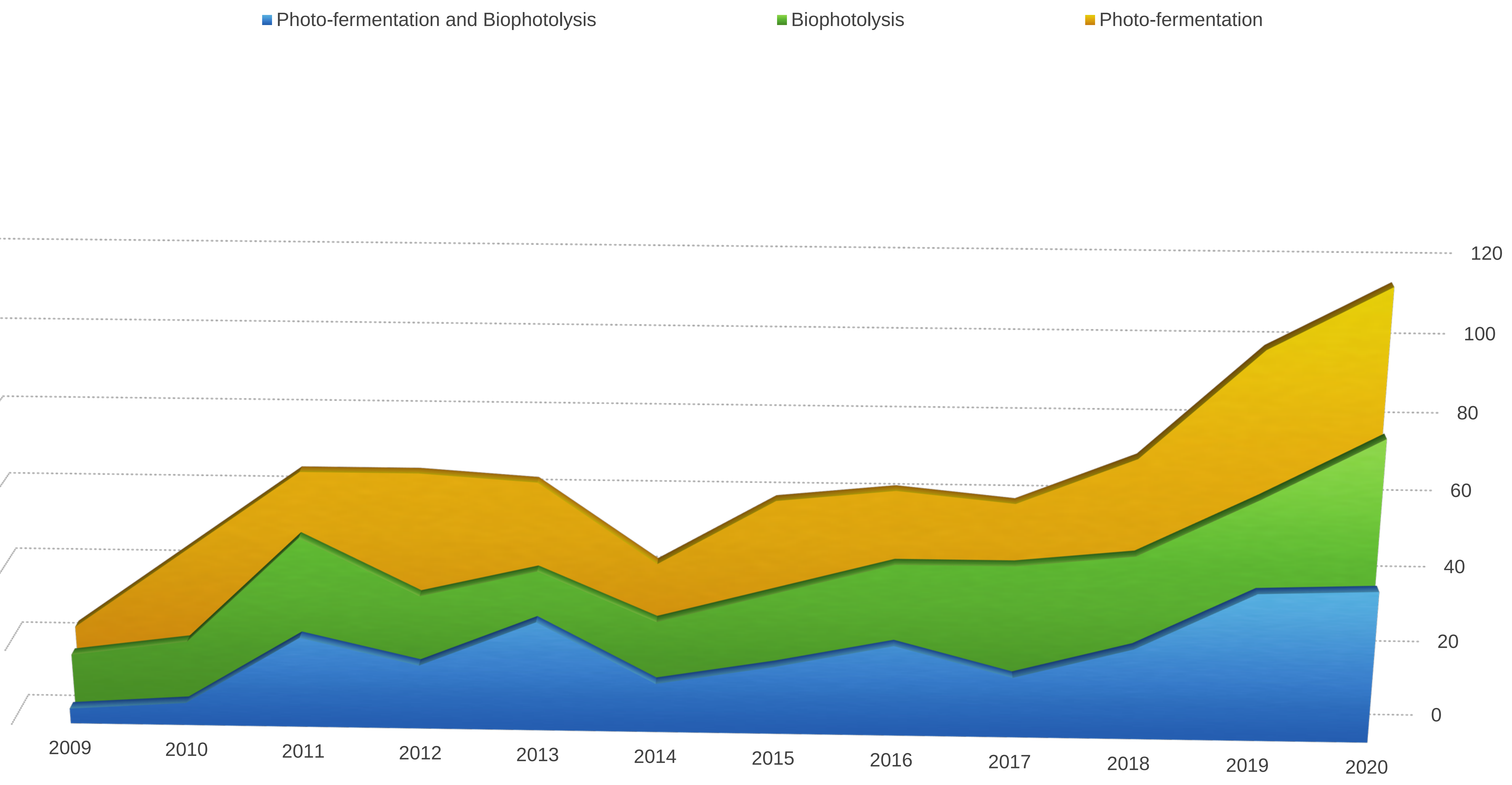
Literature Review



- Sources:
  Science Direct - Scopus
- Rise in scientific interest in biohydrogen production methods
- Photo-fermentation attracts the greatest part of research

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Biophotolysis

- Make use of the metabolic processes of microorganisms.
- Cyanobacteria - Microalgae (Anaerobic Conditions)

$$H_2O \xrightarrow{\text{Light Energy}} H_2 + O_2$$

Two different methods

Direct Biophotolysis

Indirect Biophotolysis

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Photo-fermentation

- Make use of the metabolic processes of PNS bacteria

$$\text{Carbon Source} + H_2O \xrightarrow{\text{Light Energy}} H_2 + CO_2$$

- Carbon source : Organic Acids - Different types of organic wastes
- PNS bacteria catalyze the reaction
- Anaerobic Conditions

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Process Parameters

- Carbon Source (Substrate)
- Photobioreactor Design
- Operation Mode
- pH
- Temperature
- Light illumination-intensity
- C/N ratio
- Nutrients-Inhibitors

→ Bioprocesses
Polyparametric system

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Technical Parameters

- Substrate
  - → Organic Acids (Acetate, Butyrate, Malate)
  - → Organic originated wastes - sustainable alternative
- Photobioreactor
  - → Open System - Continuous Operation
  - → Closed System - Different types of operation
- Operation Mode
  - → Batch - Widely used in lab experiments (Easily Monitored Conditions)
  - → Continuous mode - Favorable in large scale (Low energy-operation costs)

Conditions (1)

- pH: Acidophilic microorganisms

Bacteria/Algae	pH range	References
Clostridium Species	5-6	G. Kumaravel Dinesh et al 2018
Rhodobacter sphaeroides	6,8-7,2	Shiladitya Ghosh et al 2016
Chlamydomonas reinhardtii	7	Shitralekha Nag Dasgupta et al 2010
Cyanobacterium Synechocystis and Cyanobacterium Gleocapsa	6,8-8,3	Kenzhegul Bolatkhan et al 2019
Oleaginous Microalgae	6,8	Dennapa Sengmee et al, 2016

- C/N ratio:

- Important factor for nitrogenase enzyme and PNSB's.
- N_2 - Anaerobic conditions maintenance.
- N_2 - Process Inhibitor (Nitrogenase).

Optimally → C/N = 25

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Conditions (2)

- Temperature:
  - Controls the metabolic processes (path) of the enzymes.
  - Range of different microorganisms - Different optimal temperature.

Bacteria/Algae	Temperature (°C)	References
MIcroalgae	20-30	Ela Eroglu and Anastasios Melis, 2016
Cyanobacteria	25-55	Shitralekha Nag Dasgupta et al 2010, M.Y. Azwar et al, 2013
PNS bacteria	25-35	Ming Foong Tiang et al, 2020

Biophotolysis ← Microalgae, Cyanobacteria

Photo-fermentation ← PNS bacteria

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Conditions (3)

* Light illumination:
- Energy supply in the form of ATP.
- Natural / Artificial Source
- Light intensity ↑ - Biohydrogen Productivity ↑

Until

↓

Saturation Point

PNS bacteria
- 4000 - 5000 lux
- Visible + UV

Biophotolysis
- 50 - 200 μE/(m^2 * s)
- Low conversion Efficiency

Nutrients - Inhibitors

Chemicals	Improving	Inhibiting	Chemicals	Improving	Inhibiting
Iron	✓	-	Ethanol	✓	✓
Molybdenum	✓	✓	NaCl	✓	-
Nickel	✓	✓	Nano Ti-0_2	✓	-
EDTA	✓	✓	Methanol	-	✓
Vitamins	✓	-	Cooper ions	-	✓
Buffer Solutions	✓	-	Sulfide ions	-	✓
Magnesium	✓	-	Yeast	✓	✓

Experimental Data (1)

- Data presentation for biohydrogen production from microalgae and cyanobacteria

Microalgae

Cyanobacteria

Strain	Light Intensity	Temperature	pH	Biohydrogen production rate	Reference
Chlamydomonas MGA 161	115 μE / m^2 / s	30°C	8	4,48 ml / (L*h)	M.Y. Azwar et al, 2013
Chlamydomonas reinhardtii CC-124	140 μmol photons / (m^2 * s) - both sides	28°C	7,2	7,5 ml / (L*h)	Ela Eroglu and Anastasios Melis, 2016
Chlamydomonas reinhardtii 137c	110 μE / m^2 / s	25°C	7,2	2,5 ml / (L*h)	M.Y. Azwar et al, 2013
Chlamydomonas reinhardtii CC-1036	120 μmol photons / (m^2 * s)	27-29°C	7	9,2 ml / (L*h)	Ela Eroglu and Anastasios Melis, 2016
Synechocystis sp. PCC 6803	90 μE / m^2 / s	30°C	-	18,4 μl / (mg Chl * h)	Bekzhan D. Kossalbayev et al, 2020
Anabaena cylindrica	140 μE * m^{-2} * s^{-1}	-	30 ml /(L*h)	S.N.A Rahman et al, 2016	Anabaena cylindrica
Anabaena variabilis ATCC 29413	110-120 μE / m^2 / s	30°C	14,9 ml / (L*h)	M.Y. Azwar et al, 2013	Anabaena variabilis ATCC 29413

Experimental Data (2)

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- Data presentation for biohydrogen production from PNS bacteria.

Bacterial Strain	Substrate	Process	Light Intensity	Biohydrogen production rate / yield	Reference
Rhodopseudomonas palustris WP3–5	Butyric acid	Batch	135 μE * m^{-2} * s^{-1}	24,9 ml / (L*h)	S.N.A Rahman et al, 2016
R. sphaeroides ZX-5	Lactate	Batch	-	103 ml / (L*h)	Xu Li et al, 2009
R. sphaeroides ZX-5	Butyrate	Batch	-	118 ml / (L*h)	Xu Li et al, 2009
Rhodopseudomonas faecalis RLD-53	Acetate	Batch	150 W / m^2	36,60 ml / (L*h)	S.N.A Rahman et al, 2016
Rhodobacter sphaeroides ZX-5	Malate	Batch	68 μE * m^{-2} * s^{-1}	102,33 ml / (L*h)	S.N.A Rahman et al, 2016
Rhodobacter capsulatus ST410	Malate	-	66 W / m^2	100 ml / (L*h)	Shitralekha Nag Dasgupta et al 2010
Rhodobacter sphaeroides KD131	Succinate	Continuous	-	2,3 mol / mol substrate	M.Y. Azwar et al, 2013
Rhodovulum sulfidophilum P5	Glucose	Batch	100 mmol photons / (m^2 * s)	7,07 mol / mol substrate	Bibi Shahine Firdaus Boodhun et al, 2017

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Waste Utilization

- Waste utilization for biohydrogen production → Circular Economy Approach
- PNS bacteria can utilize multiple substrates → Organic Wastewater
- Reduce waste treatment - disposal costs.
- Pretreatment of the food and manufacturing industry wastewaters is necessary (dilution, filtration, pH neutralization, sterilization).
- Continuous processes are feasible and favorable.

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Waste Utilization

- Wide range of waste appropriate (solid waste - wastewater - sewage sludge).
- Dark colored wastes reduce light penetration.

- Soy sauce wastewater
- Brewery wastewater
- Dairy wastewater
- POME combined with paper and pulp mill effluent
- Olive mill wastewater
- Sugar beet molasses
- Blackstrap molasses
- Tofu wastewater
- Palm oil, pulp and paper mills effluents
- Sugar refinery wastewater

Waste Utilization

Substrate (waste water or foodwaste)	Bacterial Strain	Pretreatment method	pH	Temperature	Light intensity	Biohydrogen Production yield	Reference
Soy sauce wastewater	Consortium of PNSB dominant strain: Rhodobium marinum	Autoclaving, dilution, pH neutralization	7	30	-	2,67 L H_2 / L	Shiladitya Ghosh et al, 2016
Brewery wastewater	R. sphaeroides O.U.001	Filtration and sterilization	6	-	116 W / m^2	2,2 L H_2 / L	Karen Trchounian et al, 2017
Brewery wastewaters	Rhodobacter sphaeroides O. U. 001	-	-	-	116 W / m^2	2,24 L H_2 / L	S.N.A Rahman et al, 2016
Dairy wastewater	Rhodobacter sphaeroides O.U. 001	Filtration, autoclaving, re-filtration, dilution	7-7-02	28 ± 2	-	8,6 L H_2 / L	Shiladitya Ghosh et al, 2016
POME combined with paper and pulp mill effluent	R. sphaeroides NCIMB8253	-	-	-	-	14,438 ml H_2 / ml	Pretty Mori Budiman and Ta Yeong Wu 2018
Sugar beet molasses blackstrap molasses	Rhodobacter capsulatus JP91	-	7	30	-	10,5 mol H_2 / mol sucrose	Shiladitya Ghosh et al, 2016
Palm oil, pulp and paper mills effluents	R. sphaeroides NCIMB8253	-	-	30	7000 lux	496 mL H_2 / (L*h)	Karen Trchounian et al, 2017
Tofu wastewater	R. sphaeroides RV	-	-	-	8500 lux	4,32 L H_2 / L	Ta Yeong Wu et al, 2012
POME combined with paper and pulp mill effluent	R. sphaeroides NCIMB8253	-	-	30	4000 lux	4,67 ml H_2 / ml	Bibi Shahine Firdaus Boodhun et al, 2017
Blackstrap molasses	Rhodobacter capsulatus JP91	-	7	30	-	8 mol H_2 / mol sucrose	Shiladitya Ghosh et al, 2016
Olive mill wastewater	R. sphaeroides O.U.001	-	7,2	32	200 W / m^2	39 ml H_2 / L	Karen Trchounian et al, 2017
Sugar refinery wastewater	Rhodobacter sphaeroides O. U. 001	-	-	-	200 W / m^2	16,7 mol H_2 / mol carbon	S.N.A Rahman et al, 2016

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Future Prospects

Promising steps in bio-systems development

- Optimization of cultivation techniques
- Mixed cultures
- Genetically modified bacteria enzymes
- Hybrid Systems
- Advanced photobioreactor's design and operation

Hybrid Systems

- Dark - photo hybrid system.
- 1st step: Waste processing via dark fermentation.

  Products: Biohydrogen + VFAs
- 2nd step: VFAs further utilization via photo fermentation.
- Improved biohydrogen production - conversion efficiency
- Utilization of VFAs (dark fermentation by-products).
- Increase in working process time.

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Dark-Photo System

Two different process paths

- Sequential dark-photo system
- Mixed dark-photo system

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Conclusions

- Main advantages:

  - Cheap - accessible microorganisms.
  - High thermodynamic efficiency (theoretically).
  - Nitrogen Fixation – Environmental benefits
  - Waste utilization - Circular economy approach.
- Main Drawbacks:

  - Oxygen Sensitive microorganisms + Oxygen as process byproduct.
  - Scale up operation difficulties.
  - High energy demands - Low efficiency.
  - Photobioreactor cost - specialization.

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Conclusions

- Sunlight utilization - energy conversion into fuel (biohydrogen).
- Wide range of substrate utilization (wastes).
- Enzymes metabolic processes are crucial - anaerobic systems
- Genetic engineering - Biotechnology → Enzymes modification
- Hybrid dark - photo systems → Sustainable option
- Decarbonization - Green hydrogen production

Thank you for your attention!