



Production of Hydrogen and Methane by Two Stage Fermentation of Food Waste

A thesis submitted by

Gamal Kamel Mohamed Hassan

(M.SC in chemistry 2014)
For the Requirement of the Degree

Of

Doctor of Philosophy(Ph.D)

to

Chemistry Department

Faculty of Science

Ain Shams University





Production of Hydrogen and Methane by Two Stage Fermentation of Food Waste

Submitted By

Gamal Kamel Mohamed Hassan

This Ph.D thesishas been approved for submission by supervisors:

| Thesis supervisors | APPROVED |
|---|---|
| Prof Dr. Mohamed Mahmoud Abo-Aly Professor of inorganic chemistry Faculty of Science - Ain Shams University | •••••• |
| Prof. Dr. Fatma Abd El-Hameed El-Gohary Professor of Wastewater Treatment technologies Water Pollution Research Department National Research Center | ••••••••••••••••••••••••••••••••••••••• |

Head of Chemistry Department

Prof. Dr. Ayman Ayoub Abdel-Shafi





Approval Sheet

Ph.D. Thesis

Production of Hydrogen and Methane by Two Stage Fermentation of Food Waste

Name of the candidate: *Gamal Kamel Mohamed Hassan* This thesis has been approved for submissionby:

| Thesis supervisors | SIGNATURE | |
|--|------------------|--|
| Prof. Dr. Mohamed Mahmoud Abo-Aly | | |
| Professor of Inorganic Chemistry - Faculty of Science - Ain | | |
| Shams University | | |
| Prof. Dr. Fatma Abd El-Hameed El-Gohary | | |
| Professor of Water Pollution Research - National Research | | |
| Centre | | |
| | APPROVED | |
| Government Committee | | |
| Prof. Dr. Mohamed Mahmoud Abo-Aly | | |
| Professor of Inorganic Chemistry - Faculty of Science - Ain | | |
| Shams University | | |
| Prof. Dr. Fatma Abd El-Hameed El-Gohary | | |
| Professor of Water Pollution Research - National Research | | |
| Centre | | |
| Prof. Dr. | | |
| Professor of | | |
| Dr. | | |
| Associate professor of | | |

Head of Chemistry Department Prof. Dr. Ayman Ayoub Abdel-Shafi





"انتاج الهيدروجين والميثان على مرحلتين باستخدام تخمير فضلات الطعام

•

رسالة مقدمة من جمال كامل محمد حسن (ماجستير كيمياء تحليلية ٢٠١٤)

للحصول على درجة دكتوارة الفلسفة فى العلوم (كيمياء غير عضوية) الى الى قسم الكيمياء

كلية العلوم

جامعة عين شمس



كلية العلوم

قسم الكيمياء

اسم الطالب : جمال كامل محمد حسن

الدرجة العلمية: دكتواره الفسلفة في العلوم (كيمياء)

القسم التابع له: الكيمياء

الكلية: العلوم

الجامعة: عين شمس

سنة التخرج: ٢٠٠٩

سنة المنح: ٢٠١٩



كلية العلوم قسم الكيمياء

" انتاج الهيدروجين والميثان على مرحلتين باستخدام تخمير فضلات الطعام

11

رسالة مقدمة من جمال كامل محمد حسن

| لجنة الإشراف: التوقيع | |
|-----------------------|--|
| | أد/محمد محمود ابو على |
| | ستاذ الكيمياء غير عضوية - قسم الكيمياء - كلية العلوم - |
| | جامعة عين شمس |
| | أد/ فاطمة عبد الحميد الجوهرى |
| | أستاذ باحث – بحوث تلوث المباة – المركز القومي للبحوث |

رئيس قسم الكيمياء أد/ ايمن ايوب عبد الشافي



كلية العلوم قسم الكيمياء رسالة دكتوارة الفلسفة في العلوم (كيمياء) اسم الطالب: جمال كامل محمد حسن

عنوان الرسالة:

" انتاج الهيدروجين والميثان على مرحلتين باستخدام تخمير فضلات الطعام

••

| فصص كيمياء | نواره القلسفة في العلوم ت | سم الدرجه: دكة |) |
|----------------------------|---------------------------|-------------------|----------------------------|
| | | <u>: ب</u> | لجنة الإشراة |
| | | رد ابو علی | اً.د/محمد محمو |
| | لعلوم – جامعة عين شمس | ِ عضوية - كلية اا | أستاذ الكيمياءغير |
| | ى | الحميد الجوهر | أ.د/ فاطمة عبد |
| | المركز القومي للبحوث | وث تلوث المياة - | أستاذ باحث – بح |
| | - | 4.19/ | تاريخ البحث: / |
| | | : | لجنة التحكيم |
| | | | أ.د/محمد مح <mark>د</mark> |
| | العلوم - جامعة عين شمس | ئير عضوية - كلية | أستاذ الكيمياء |
| | ی | بد الحميد الجو هر | أ.د/ فاطمة ع |
| | - المركز القومي للبحوث | حوث تلوث المياة _ | أستاذ باحث _ ب |
| | | ض امين السقا | أ.د/ رجب ريا |
| | <u>ض</u> ة | دسة _ جامعة النهو | أستاذ بكلية الهن |
| | | ید محمود ضاهر | أ.د/ احمد الس |
| | لمواد النووية | العضوية - هيئة ال | أستاذ الكيمياء غير |
| | | | الدراسات العليا: |
| | | ن الرسالة بتاريخ | ختم الإجازة :أجيزن |
| " , , , , | Y.19/ / | 4 | 1-11 1 7-11 |
| ه مجلس الجامعة / / ۷۰۰۷ | مواقف | | موافقة مجلس الكلي |
| / ۲۰۱۹ | | 1 • | ۱۹/ / |

جامعة عين شمس كلية العلوم قسم الكيمياء

شكـــر

اشكر السادة الأساتذة الذين قاموا بالإشراف وهم:

١- أ.د/محمد محمود ابو على

أستاذ الكيمياء غير عضوية - قسم الكيمياء - كلية العلوم - جامعة عين شمس

٢- أد/ فاطمة عبد الحميد الجوهري

أستاذ باحث قسم بحوث تلوث المياة - شعبة بحوث البيئة - المركز القومي للبحوث

:

ثم الأشخاص الذين تعاونوا معى فى البحث وهم: 1- أد/ الان جوى

أستاذ الهندسة – قسم الطاقة المتجددة – كلية الهندسة – جامعة جنوب ويلز

۲- د/ جیمی ماسنت

أستاذ الهندسة – قسم الطاقة المتجددة – كلية الهندسة – جامعة جنوب ويلز

:

وكذلك الهيئات الآتية:

1 - المركز القومي للبحوث

٢ - قسم بحوث تلوث المياة
٣ - كلية العلوم جامعة عين شمس
٤ - جامعة جنوب ويلز

Acknowledgments

First and foremost, all praises and sincere thanks are to **ALLAH.**

I wish to express my sincere appreciation to Prof. Dr. Mohamed Mahmoud Abo-Aly, Professor of Inorganic Chemistry, Faculty of Science, Ain Shams University, for his valuable guidance, helpful suggestions, continuous encouragement, supervision and support during this work. I would like to express my sincere thanks, full respect and deep gratitude to Prof. Dr. Fatma Abd El-Hameed El-Gohary, Professor of Water Pollution Research - National Research Centre, for her patient supervision, inspiring guidance, critical comments, suggestions, and the neverending support, she displayed throughout this study.

I sincerely express my deepest gratitude to Prof. Dr. Alan Guwy, Head of the Sustainable Environment Research Centre, Faculty of Computing, Engineering and Science, University Of South Wales, UK for hosting me for almost 2 years for doing this work. I appreciate his support, enthusiasm, and valuable discussion.

Thanks, appreciation and gratitude are due to Dr. **Jaime Massanet-Nicolau**,Sustainable Environment Research
Centre, Faculty of Computing, Engineering and Science,

University Of South Wales, UK, for providing necessary knowledge, laboratory facilities and valuable discussions during almost all of this work.

I dedicate this PhD to my mother's soul (Aisha Korny Salem). I hope my God to forgive her and this work doing as ongoing charity.

I wish to express my warm and sincere thanks and appreciation to my wife Eng. Aml Samy, for supporting me during my work. Really I don't find any word to express my thanks and my gratitude to her.

I would like to thank Water Research Department, National Research Centre and Faculty of Computing, Engineering and Science, University Of South Wales, UK and Faculty of Science, Ain Shams University, for all the facilities provided.

Finally, I would like to thank my father, my brother Hussein and his wife Heba, my sisters Nora and her husband Ramadan, Naira and Nourhan, and finally, my daughter Aisha for their love, support and devotion throughout my Ph.D. fulfillment.

Gamal Kamel Mohamed Hassan

Assistant researcher, Water Research Department, National Research Centre.

Contents

| | Page |
|--|----------|
| Contents | I-III |
| List of Tables | IV |
| List of Figures | V-IX |
| List of Abbreviations | X-XI |
| Abstract & Key words | XII-XIII |
| Summary and Conclusion | a-j |
| Chapter 1: Background and Literature Review | |
| 1.1.Background | 1 |
| 1.2 Municipal solid waste generation and distribution pattern | 2 |
| 1.2.1 Worldwide situation | 2 |
| 1.2.2 Egyptian situation | 6 |
| 1.3 Municipal solid waste composition | 8 |
| 1.3.1 Global level | 8 |
| 1.3.2 Egyptian situation | 9 |
| 1.4 Food waste | 10 |
| 1.4.1 Generation and characteristics | 10 |
| 1.4.2 Food waste treatment | 16 |
| 1.4.3 Food waste- to- energy: conversion technologies | 17 |
| 1.4.3.1 Bio-hydrogen production | 17 |
| 1.4.3.2Factors affecting bio-hydrogen production from food waste | 29 |
| 1.4.3.3 Bioreactors configuration for hydrogen fermentation | 49 |
| Chapter 2: Materials and Methods | |
| 2.1 Experimental set-up | 57 |
| 2.1.1 Two-stage Upflow Aerobic Biofilter Reactor | 57 |

| (UABR) | |
|--|----|
| 2.1.2 Packing materials | 60 |
| 2.1.3 Continuous stirred tank reactors (CSTR) | 60 |
| 2.1.4 Removal of VFAs via Electrodialysis (ED) | 63 |
| 2.2 Inoculum for systems (UABR and CSTR) | 65 |
| 2.3 Analytical methods and calculations | 65 |
| 2.4 Bacterial isolation and identification from hydrogen and methane reactors. | 66 |
| 2.5 Food waste used for the systems | 67 |
| 2.5.1 UABR | 67 |
| 2.5.2 CSTR | 67 |
| 2.6 Operating conditions | 69 |
| 2.6.1 Strategy of the Operation of the Two-stage UABR | 69 |
| 2.6.1.1 Impact of pH values on hydrogen and methane Production. | 69 |
| 2.6.1.2. Impact of HRT values on hydrogen and methane production from UABR fed by FW. | 70 |
| 2.6.1.3 Impact of temperature on hydrogen production | 70 |
| 2.6.1.4 Impact of organic loading rate (OLR) values on hydrogen and methane production from UABR | 70 |
| 2.6.2 Strategy of CSTR operation | 71 |
| 2.6.2.1 Impact of ED on hydrogen production from food waste. | 71 |
| 2.6.2.2 Impact of ED on hydrogen and methane production from FW via two stages. | 71 |
| Chapter 3: Results and discussions | |
| 3.1 Physico-chemical characteristics of feedstock | 73 |
| 3.2 Impact of pH and HRT values on hydrogen and methane production using two-stage UABR | 83 |
| 3.2.1 Impact of pH | 83 |
| 3.2.1.1 Performance of hydrogen reactor | 83 |
| 3.2.1.2 Performance of methane reactor | 84 |

| 3.2.2 Impact of HRT | 85 |
|---|-----|
| 3.2.2.1 Performance of hydrogen reactor | 85 |
| 3.2.2.2 Performance of methane reactor | 85 |
| 3.2.3 Identification of the bacterial isolates in the hydrogen and methane reactors. | 87 |
| 3.2.4 Characteristics of reactors effluents | 89 |
| 3.3 Impact of In situ Aeration at Different Operating Temperatures. | 93 |
| 3.3.1 Effluent Characteristics | 96 |
| 3.4 Impact of Organic Loading Rate on hydrogen and methane production via two stage fermentation of UABR. | 98 |
| 3.4.1 Performance of hydrogen reactor | 98 |
| 3.4.2 Performance of methane reactor | 99 |
| 3.4.3 Effluent Characteristics | 102 |
| 3.4.4Microbiological examination of sludge at optimum temperature and OLR | 105 |
| 3.4.5 Hydrogen, Methane and Energy yields for food waste at the optimum conditions (Temperature 45°C, OLR 20 g COD/l.d and pH 5.5). | 106 |
| 3.5 Characteristics of food waste used for CSTR. | 108 |
| 3.6 Hydrogen production performance in CSTR | 113 |
| 3.6.1 Control phase | 113 |
| 3.6.2 ED phase | 113 |
| 3.6.3 Production of VFAs | 115 |
| 3.6.4 Treatment efficiency | 117 |
| 3.7 Impact of ED on hydrogen and methane production from FW via two stages CSTR at optimum temperature and OLR. | 119 |
| 3.7.1 Hydrogen reactor | 119 |
| 3.7.2 Methane reactor | 122 |
| 3.7.3 Production of VFAs in H2 and CH4-producing reactors at optimum temperature and OLR | 123 |
| 3.7.4 Treatment utilization via H2 and CH4 stages at | 128 |

| optimum OLR and temperature. | |
|---|-----|
| 3.7.5 Calculation of the total energy yield from the FW via two-stage fermentation. | 129 |
| References | 132 |
| الملخص العربي | 166 |

List of Tables

| Table | | Page |
|-------|--|------|
| 2.1 | Constituents of synthetic food waste used as feedstock for the CSTR | 68 |
| 3.1 | Physico-chemical Characteristics of the Raw food waste | 74 |
| 3.2 | Most Dominant Bacterial Strains in the Biomass Samples Collected from Hydrogen and Methane Reactors | 89 |
| 3.3 | Performance of the two stage UABR fed with FW at the same dilution (1 FW: 10Water) with different pH and HRT | 91 |
| 3.4 | Characteristics of the UABR Effluents at different temperatures. | 97 |
| 3.5 | Performance of the two stage UABR fed with food waste at different OLR. | 104 |
| 3.6 | Energy yield from food waste by two stages at OLR=20 g-COD/l.day and Temperature 45 °C | 107 |
| 3.7 | Physico-chemical characteristics of the raw food waste used in CSTR. | 109 |
| 3.8 | Composition of reactor contents during each experimental phase. | 118 |