

**PREPARATION, CHARACTERIZATION, PROPERTIES AND  
DEGRADATION BEHAVIOUR OF PEANUT SHELL POWDER/  
RECYCLED POLYPROPYLENE COMPOSITES**

by

**NOR FASIAH BINTI ZAABA**

**Thesis submitted in fulfillment of the  
requirements for the degree of  
Doctor of Philosophy**

**January 2017**

## ACKNOWLEDGEMENTS

First and foremost, my utmost gratitude and praise is to Allah, the Most Merciful and Most Compassionate for His blessings, that I was able to complete this research work. I feel so blessed for the given opportunity and granting the capability to proceed successfully. Completing my PhD degree is probably the most challenging activity of my 29 years of life. The best and worst moments of my doctoral journey have been shared with many people. I would like to express my sincere gratitude to all of them.

To my PhD supervisor, Prof. Dr. Hanafi Bin Ismail, I am extremely grateful for his valuable guidance, scholarly inputs and consistent encouragement I received throughout the research work. It is a great opportunity to do my doctoral program under his supervision and to learn from his research expertise. I also would like to express my gratitude to the one who always has confidence in me, Prof. Ir. Dr. Mariatti Bt Jaafar. She was among those who kept me going at the beginning, who was the source of inspiration since the early days, and who taught me many things, including academic and career planning, personal related matters as well as life and spiritual conduct.

Most of the results described in this thesis would not have been obtained without a close collaboration with few laboratories. I owe a great deal of appreciation and gratitude to Mr. Shahril Amir bin Saleh and Mr. Mohd Suharuddin Bin Sulong (Rubber Lab), Mr. Mohammad Bin Hassan (Plastic Lab), Mr. Mohd Faizal Bin Mohd Kassim (Latex Lab), Mr. Abdul Rashid Bin Selamat and Mr. Muhammad Khairi Bin Khalid (SEM Lab), Mr. Norshahrizol Bin Nordin (Workshop) as well as Mr. Mokhtar Bin Mohamad (Metallographic Lab) for their help and support during my experimentation in those laboratories. Besides, I would like to thank administrative and technical staff members of the SMMRE, USM who has been kind enough to advise and help in their

respective roles. I am indebted to my research group colleagues for providing a stimulating and fun filled environment. Many thanks go in particular to Shazlin Bt Shaari, Norshahida Bt Sarifuddin , Teo Pao Ter, Ooi, Mathialagan Muniyadi, Pang Ai Ling, Dalina Bt Samsudin, Faiezah Bt Hashim, Siti Zuliana Bt Salleh, Komethi Muniandy, Noranizah Bt Mohamad Aini for their personal and scholarly interaction. Words are short to express my deep sense of gratitude towards my following friends. Many thanks go to fellow friends who give their ears to listen to, their shoulders to cry on, their hearts to care specially Nursyazalina Bt Mustafa, Nurayuni Bt Syukor, Noor Izzati Bt Muhd Nasir and Muhammad Ariff Bin Abdul Razak for this twenty years' friendship and for their constant support in every way.

A gratefully wonderful thanks belong to my little caliph, Zayyan Zill Qayyim Bin Zakir Irman. Thank you for being my new inspiration and motivation in performing my best in every single thing I do.

My special words of heartiest appreciation also dedicated to my beloved husband, Zakir Irman Bin Sozaini, my late dearest father, Allahyarham Zaaba Bin Osman, my lovely mother, Khadijah Bt Mohamed, my father and mother-in-law, Sozaini Bin Ali and Jarinah Bt Sultan for their non-stop encouragement and support to me through laugh and tears. I will never forget what we've gone through in some phase of life emotionally and financially, and that made me really appreciate this pathway. Besides, my special thanks also dedicated to my brother Ahmad Fairus Bin Zaaba , my sisters-in-law Rogayah Bt Ramli and Zarini Izzati Bt Sozaini for their care and love. Finally, I am also grateful to the financial support received through MyBrain15 from the Ministry of Education of Malaysia and Cluster for Polymer Composites (CPC) and Solid Waste Management (SWM USM) Grant.

## TABLE OF CONTENTS

|  | Page  |
|--|-------|
| <b>ACKNOWLEDGEMENTS</b>                      | ii    |
| <b>TABLE OF CONTENTS</b>                     | iv    |
| <b>LIST OF TABLES</b>                        | xi    |
| <b>LIST OF FIGURES</b>                       | xiii  |
| <b>LIST OF ABBREVIATIONS</b>                 | xxi   |
| <b>LIST OF SYMBOLS</b>                       | xxiii |
| <b>ABSTRAK</b>                               | xxv   |
| <b>ABSTRACT</b>                              | xxvii |
| <b>CHAPTER ONE: INTRODUCTION</b>             |       |
| 1.1 Overview                                 | 1     |
| 1.2 Problem Statements                       | 3     |
| 1.3 Research Objectives                      | 7     |
| 1.4 Thesis Outline                           | 8     |
| <b>CHAPTER TWO: LITERATURE REVIEW</b>        |       |
| 2.1 Plastic and Recycling                    | 11    |
| 2.1.1 Challenges and Opportunities           | 12    |
| 2.1.2 Waste Management Strategies            | 14    |
| 2.2 Polypropylene and Recycled Polypropylene | 16    |

|       |  |    |
|-------|--|----|
| 2.2.1 | Structure                                | 18 |
| 2.2.2 | Properties and Application               | 18 |
| 2.3   | Thermoplastic/Natural Filler Composites  | 19 |
| 2.3.1 | Challenges                               | 23 |
| 2.3.2 | Current Developments                     | 24 |
| 2.4   | Peanut Shell Powder as Natural filler    | 25 |
| 2.4.1 | Structure and Chemistry                  | 26 |
| 2.4.2 | Properties and Application               | 29 |
| 2.5   | Chemical Modification                    | 29 |
| 2.5.1 | Compatibilization with PEAA              | 30 |
| 2.5.2 | Filler Modification by Polyvinyl Alcohol | 31 |
| 2.5.3 | Alkaline Peroxide Pre-treatment          | 32 |
| 2.6   | Radiation on Polymers                    | 33 |
| 2.6.1 | Electron Beam Irradiation                | 34 |
| 2.7   | Plastic Degradation                      | 35 |
| 2.7.1 | Photo-oxidative Degradation              | 36 |
| 2.7.2 | Thermal Degradation                      | 36 |
| 2.8   | Plastic Degradation Testing              | 37 |
| 2.8.1 | Natural Weathering Testing               | 37 |

### **CHAPTER THREE : METHODOLOGY**

|       |                                |    |
|-------|--------------------------------|----|
| 3.1   | Introduction                   | 41 |
| 3.2   | Raw materials                  | 41 |
| 3.2.1 | Recycled Polypropylene         | 42 |
| 3.2.2 | Peanut Shell Powder            | 42 |
| 3.2.3 | Poly(ethylene-co-acrylic acid) | 43 |

|        |   |    |
|--------|---|----|
| 3.2.4  | Polyvinyl Alcohol   | 44 |
| 3.2.5  | Hydrogen Peroxide   | 44 |
| 3.2.6  | Sodium Hydroxide  | 45 |
| 3.2.7  | Acetic Acid   | 45 |
| 3.3    | Instrument  | 46 |
| 3.4    | Natural Filler Preparation  | 47 |
| 3.4.1  | Preparation of PSP  | 47 |
| 3.4.2  | Modification of PSP with PVOH                                       | 47 |
| 3.4.3  | Pre-treatment of PSP by Alkaline Peroxide                           | 47 |
| 3.5    | Fabrication of Composites   | 48 |
| 3.5.1  | RPP/PSP and RPP/PSP/PEAA Composites                                 | 49 |
| 3.5.2  | RPP/PSP Composites with PVOH  | 49 |
| 3.5.3  | RPP/PSP Composites with H <sub>2</sub> O <sub>2</sub> Pre-treatment | 50 |
| 3.6    | Shaping   | 51 |
| 3.7    | Tensile Test  | 51 |
| 3.8    | Morphology Test   | 51 |
| 3.9    | Fourier Transform Infrared (FTIR) Spectroscopy                      | 52 |
| 3.10   | Water Absorption  | 52 |
| 3.11   | Thermogravimetric Analysis (TGA)                                    | 52 |
| 3.12   | Differential Scanning Calorimetry (DSC)                             | 52 |
| 3.13   | Degradation Test  | 53 |
| 3.13.1 | Natural Weathering Test   | 53 |
| 3.14   | Determination of Degradation  | 55 |
| 3.14.1 | Tensile Properties  | 55 |
| 3.14.2 | Surface Morphology  | 55 |

|        |   |    |
|--------|---|----|
| 3.14.3 | Carbonyl Indices                        | 55 |
| 3.14.4 | Differential Scanning Calorimetry (DSC) | 56 |
| 3.14.5 | Weight Loss                             | 56 |
| 3.15   | Electron Beam Irradiation               | 56 |
| 3.15.1 | Gel Content Analysis                    | 57 |

## **CHAPTER FOUR: EFFECT OF PEAA ON PROPERTIES OF RPP/PSP COMPOSITES**

|       |  |    |
|-------|--|----|
| 4.1   | Poly(ethylene-co-acrylic acid) as Compatibilizer                           | 58 |
| 4.1.1 | Processing Parameters  | 58 |
| 4.1.2 | Tensile Properties   | 61 |
| 4.1.3 | Morphological Properties   | 65 |
| 4.1.4 | Fourier Transform Infrared (FTIR) Spectroscopy                             | 68 |
| 4.1.5 | Water Absorption   | 70 |
| 4.1.6 | Differential Scanning Calorimetry  | 73 |
| 4.1.7 | Thermogravimetric Analysis   | 75 |
| 4.2   | Effect of Natural Weathering on the PEAA Compatibilized RPP/PSP Composites | 77 |
| 4.2.1 | Visual Observation   | 77 |
| 4.2.2 | Tensile Properties   | 79 |
| 4.2.3 | Morphology of Weathered Samples  | 83 |
| 4.2.4 | Carbonyl Indices   | 86 |
| 4.2.5 | Differential Scanning Calorimetry (DSC)                                    | 89 |
| 4.2.6 | Weight Loss  | 92 |

## **CHAPTER FIVE: EFFECT OF PVOH ON PROPERTIES OF RPP/PSP COMPOSITES**

|       |   |     |
|-------|---|-----|
| 5.1   | Modification of PSP by Using Polyvinyl Alcohol              | 93  |
| 5.1.1 | Processing Parameters                                       | 93  |
| 5.1.2 | Tensile Properties  | 95  |
| 5.1.3 | Morphological Properties                                    | 99  |
| 5.1.4 | Fourier Transform Infrared (FTIR) Spectroscopy              | 101 |
| 5.1.5 | Water Absorption  | 103 |
| 5.1.6 | Differential Scanning Calorimetry                           | 105 |
| 5.1.7 | Thermogravimetric Analysis                                  | 108 |
| 5.2   | Effect of Natural Weathering on the RPP/PSP/PVOH Composites | 110 |
| 5.2.1 | Visual Observation  | 110 |
| 5.2.2 | Tensile Properties  | 111 |
| 5.2.3 | Morphology of Weathered Samples                             | 116 |
| 5.2.4 | Carbonyl Indices  | 117 |
| 5.2.5 | Differential Scanning Calorimetry (DSC)                     | 120 |
| 5.2.6 | Weight Loss   | 123 |

## **CHAPTER SIX: EFFECT OF ALKALINE PEROXIDE PRE-TREATMENT ON PROPERTIES OF RPP/PSP COMPOSITES**

|       |   |     |
|-------|---|-----|
| 6.1   | Pre-treatment of PSP by Using Alkaline Peroxide | 125 |
| 6.1.1 | Processing Parameters                           | 125 |
| 6.1.2 | Tensile Properties                              | 127 |
| 6.1.3 | Morphological Properties                        | 131 |
| 6.1.4 | Fourier Transform Infrared (FTIR) Spectroscopy  | 132 |



|       |  |     |
|-------|--|-----|
| 6.1.5 | Water Absorption   | 134 |
| 6.1.6 | Differential Scanning Calorimetry  | 136 |
| 6.1.7 | Thermogravimetric Analysis   | 138 |
| 6.2   | Effect of Natural Weathering on the RPP/PSP/H <sub>2</sub> O <sub>2</sub> Composites | 140 |
| 6.2.1 | Visual Observation   | 141 |
| 6.2.2 | Tensile Properties   | 141 |
| 6.2.3 | Morphology of Weathered Samples  | 145 |
| 6.2.4 | Carbonyl Indices   | 147 |
| 6.2.5 | Differential Scanning Calorimetry (DSC)  | 149 |
| 6.2.6 | Weight Loss  | 152 |

**CHAPTER SEVEN: EFFECT OF ELECTRON BEAM IRRADIATION  
ON PROPERTIES OF RPP/PSP COMPOSITES**

|       |  |     |
|-------|--|-----|
| 7.1   | Electron Beam Irradiation on RPP/PSP Composites                      | 153 |
| 7.1.1 | Tensile Properties   | 153 |
| 7.1.2 | Morphological Properties   | 157 |
| 7.1.3 | Fourier Transform Infrared (FTIR) Spectroscopy                       | 160 |
| 7.1.4 | Water Absorption   | 161 |
| 7.1.5 | Differential Scanning Calorimetry                                    | 163 |
| 7.1.6 | Thermogravimetric Analysis   | 166 |
| 7.2   | Effect of Natural Weathering on the Irradiated RPP/PSP<br>Composites | 168 |
| 7.2.1 | Tensile Properties   | 168 |
| 7.2.2 | Morphology of Weathered Samples                                      | 172 |
| 7.2.3 | Carbonyl Indices   | 174 |
| 7.2.4 | Differential Scanning Calorimetry (DSC)                              | 176 |

|       |             |     |
|-------|-------------|-----|
| 7.2.5 | Weight Loss | 179 |
|-------|-------------|-----|

**CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS**

|     |                                  |     |
|-----|----------------------------------|-----|
| 8.1 | Conclusions                      | 181 |
| 8.2 | Recommendations for Future Study | 182 |

|                   |            |
|-------------------|------------|
| <b>REFERENCES</b> | <b>184</b> |
|-------------------|------------|

**LIST OF PUBLICATIONS AND CONFERENCE PROCEEDING**

## LIST OF TABLES

|            |  | Page |
|------------|--|------|
| Table 2.1  | Recent reported work on natural fillers and polymer composites (Source: <a href="http://www.sciencedirect.com">www.sciencedirect.com</a> ; keywords: natural filler, polymer composites) | 22   |
| Table 3.1  | List of raw materials  | 41   |
| Table 3.2  | RPP information  | 42   |
| Table 3.3  | PSP information  | 43   |
| Table 3.4  | PEAA information   | 44   |
| Table 3.5  | PVOH information   | 44   |
| Table 3.6  | Hydrogen peroxide information  | 45   |
| Table 3.7  | Sodium hydroxide information   | 45   |
| Table 3.8  | Acetic acid information  | 46   |
| Table 3.9  | Instruments used in this research  | 46   |
| Table 3.10 | Formulation of RPP/PSP composites with the presence of PEAA  | 49   |
| Table 3.11 | Formulation of RPP/PSP and RPP/PSP/PVOH composites   | 50   |
| Table 3.12 | Formulation of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites  | 50   |
| Table 4.1  | DSC data of uncompatibilized and compatibilized RPP/PSP composites   | 75   |
| Table 4.2  | TGA data of uncompatibilized and compatibilized RPP/PSP composites   | 77   |
| Table 4.3  | Retention of tensile properties for RPP/PSP composites after 6 months weathering   | 81   |
| Table 4.4  | DSC data of uncompatibilized and compatibilized RPP/PSP composites after 6 months weathering   | 91   |

|           |  |     |
|-----------|--|-----|
| Table 4.5 | Weight loss of uncompatibilized and compatibilized RPP/PSP composites over 6 months of weathering                          | 92  |
| Table 5.1 | DSC data of RPP/PSP and RPP/PSP/PVOH composites  | 107 |
| Table 5.2 | TGA data of RPP/PSP and RPP/PSP/PVOH composites  | 110 |
| Table 5.3 | Retention of tensile properties for RPP/PSP and RPP/PSP/PVOH composites after 6 months weathering                          | 115 |
| Table 5.4 | DSC data of RPP/PSP and RPP/PSP/PVOH composites after natural weathering   | 123 |
| Table 5.5 | Weight loss of RPP/PSP and RPP/PSP/PVOH composites   | 124 |
| Table 6.1 | DSC data of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites   | 138 |
| Table 6.2 | TGA data of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites   | 140 |
| Table 6.3 | Retention of tensile properties for RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites after 6 months weathering | 143 |
| Table 6.4 | DSC data of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites after natural weathering                                      | 151 |
| Table 6.5 | Weight loss of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites over 6 months of weathering                    | 152 |
| Table 7.1 | DSC data of non-irradiated and irradiated RPP/PSP composites   | 164 |
| Table 7.2 | TGA data of non-irradiated and irradiated RPP/PSP composites   | 168 |
| Table 7.3 | Retention of tensile properties for non-irradiated and irradiated RPP/PSP composites after 6 months weathering             | 170 |
| Table 7.4 | DSC data of irradiated RPP/PSP composites after 6 months exposure to natural weathering                                    | 179 |
| Table 7.5 | Weight loss of non-irradiated and irradiated RPP/PSP composites  | 180 |

## LIST OF FIGURES

|            |   | Page |
|------------|---|------|
| Figure 2.1 | Plastic waste recycling route: collection, sorting and processing (adapted from <a href="http://www.ibhangarwala.com">www.ibhangarwala.com</a> )  | 14   |
| Figure 2.2 | Isomerism for positions in polypropylene (a) head-to-tail; (b) head-to-head; (c) tail-to-tail (adapted from <a href="http://www.pslc.ws/macrog/pp.htm">http://www.pslc.ws/macrog/pp.htm</a> )   | 18   |
| Figure 2.3 | Number of journals published on the natural fillers and polymer composites. (Source: <a href="http://www.sciencedirect.com">www.sciencedirect.com</a> ; keywords: natural filler, polymer composites)                                 | 22   |
| Figure 2.4 | (a) Application areas and (b) countries share for thermoplastic/natural filler composites (adapted from <a href="http://www.intechopen.com">www.intechopen.com</a> )  | 25   |
| Figure 2.5 | Structure of lignocellulose (adapted from <a href="http://www.nature.com">www.nature.com</a> )  | 27   |
| Figure 2.6 | Structure of lignocellulose (adapted from <a href="http://www.nature.com">www.nature.com</a> )  | 28   |
| Figure 2.7 | Positioning of the cellulose fibrils in lignocellulose: (M) Middle lamella; (P) Primary wall; (S1) Secondary wall; (S2) Secondary wall II; (S3) Secondary wall III (adapted from <a href="http://www.nature.com">www.nature.com</a> ) | 29   |
| Figure 2.8 | Typical photo-degradation process of polymer (Singh & Sharma, 2008)   | 38   |
| Figure 2.9 | Typical UV degradation on natural filler/polymer composites and its component (Azwa et al., 2013)   | 40   |
| Figure 3.1 | SEM micrograph of the irregular morphology of peanut shell powder   | 43   |
| Figure 3.2 | Average temperature during outdoor natural weathering test from June to December 2015   | 54   |
| Figure 3.3 | Average rainfall during outdoor natural weathering test from June to December 2015  | 54   |
| Figure 3.4 | Schematic diagram of electron beam accelerators irradiating composite samples   | 57   |

|             |  |    |
|-------------|--|----|
| Figure 4.1  | The processing torque of compatibilized RPP/PSP composites   | 59 |
| Figure 4.2  | The stabilization torque of RPP/PSP composites with and without compatibilizer at different PSP loadings                           | 61 |
| Figure 4.3  | Tensile strength of RPP/PSP composites with and without compatibilizer at different PSP loading                                    | 63 |
| Figure 4.4  | Elongation at break of RPP/PSP composites with and without compatibilizer at different PSP loadings                                | 64 |
| Figure 4.5  | Tensile modulus of RPP/PSP composites with and without compatibilizer at different PSP loadings                                    | 65 |
| Figure 4.6  | Tensile fractured surface of uncompatibilized RPP/PSP composites at (a) 0 wt.%, (b) 10 wt.%, (c) 20wt.% and (d) 40wt.% PSP loading | 67 |
| Figure 4.7  | Tensile fractured surface of compatibilized RPP/PSP composites at (a) 10 wt.%, (b) 20 wt.% and (c) 40 wt.% PSP loading             | 68 |
| Figure 4.8  | IR spectra of RPP/PSP composites (a) uncompatibilized and (b) compatibilized with PEAA   | 69 |
| Figure 4.9  | Formation of ester group between PEAA and PSP during mixing  | 70 |
| Figure 4.10 | Water uptake of uncompatibilized RPP/PSP composites at different PSP loading   | 71 |
| Figure 4.11 | Equilibrium water uptake of RPP/PSP composites at 30 days with and without compatibilizer  | 72 |
| Figure 4.12 | Heating thermogram of uncompatibilized and compatibilized RPP/PSP composites   | 73 |
| Figure 4.13 | Cooling thermogram of uncompatibilized and compatibilized RPP/PSP composites   | 74 |
| Figure 4.14 | TG thermograms of compatibilized RPP/PSP composites  | 76 |
| Figure 4.15 | DTG thermograms of compatibilized RPP/PSP composites   | 76 |

|             |  |    |
|-------------|--|----|
| Figure 4.16 | Visual observation of uncompatibilized RPP/PSP composites at various PSP loading after 6 months exposure to natural weathering                               | 78 |
| Figure 4.17 | Visual observation of compatibilized RPP/PSP composites at various PSP loading after 6 months exposure to natural weathering                                 | 79 |
| Figure 4.18 | Comparison of tensile strength after 6 months of natural weathering  | 80 |
| Figure 4.19 | Comparison of elongation at break after 6 months of natural weathering   | 82 |
| Figure 4.20 | Comparison of tensile modulus after 6 months of natural weathering   | 83 |
| Figure 4.21 | SEM micrographs of weathered surface for uncompatibilized composites with (a) 10 wt.%, (b) 30 wt.%, and (c) 40 wt.% PSP loading after 6 months of weathering | 85 |
| Figure 4.22 | SEM micrographs of weathered surface for compatibilized composites with (a) 10 wt.%, (b) 30 wt.%, and (c) 40 wt.% PSP loading after 6 months of weathering   | 86 |
| Figure 4.23 | IR spectra of uncompatibilized composites over 6 months of weathering  | 87 |
| Figure 4.24 | IR spectra of compatibilized composites over 6 months of weathering  | 88 |
| Figure 4.25 | CI for uncompatibilized and compatibilized composites over a period of weathering for 6 months.  | 89 |
| Figure 4.26 | Heating thermogram of compatibilized composites before and after weathering  | 90 |
| Figure 4.27 | Cooling thermogram of compatibilized composites before and after weathering  | 90 |
| Figure 5.1  | The processing torque of RPP/PSP/PVOH composites at different PSP loading  | 94 |
| Figure 5.2  | Stabilization torque of RPP/PSP and RPP/PSP/PVOH composites at different PSP loading   | 95 |

|             |  |     |
|-------------|--|-----|
| Figure 5.3  | Tensile strength of RPP/PSP and RPP/PSP/PVOH composites at different PSP loading                                   | 97  |
| Figure 5.4  | Elongation at break of RPP/PSP and RPP/PSP/PVOH composites at different PSP loading                                | 98  |
| Figure 5.5  | Tensile modulus of RPP/PSP and RPP/PSP/PVOH composites at different PSP loading                                    | 98  |
| Figure 5.6  | SEM micrographs of RPP/PSP composites at (a) 10%, (b) 20%, and (c) 40% filler loading by weight                    | 100 |
| Figure 5.7  | SEM micrographs of RPP/PSP/PVOH composites at (a) 10%, (b) 20%, and (c) 40% filler loading by weight               | 101 |
| Figure 5.8  | IR spectra of (a) RPP/PSP and (b) RPP/PSP/PVOH composites  | 102 |
| Figure 5.9  | Proposed interaction of PSP/PVOH with RPP matrix   | 103 |
| Figure 5.10 | Water uptake over 30 days of RPP/PSP composites at different PSP loading   | 104 |
| Figure 5.11 | Equilibrium water uptake of RPP/PSP and RPP/PSP/PVOH composites at 30 days   | 105 |
| Figure 5.12 | Heating thermogram of RPP/PSP and RPP/PSP/PVOH composites  | 106 |
| Figure 5.13 | Cooling thermogram of RPP/PSP and RPP/PSP/PVOH composites  | 106 |
| Figure 5.14 | TG thermograms of RPP/PSP/PVOH composites  | 109 |
| Figure 5.15 | DTG thermograms of RPP/PSP/PVOH composites   | 109 |
| Figure 5.16 | Visual observation of RPP/PSP/PVOH composites at various PSP loading after 6 months exposure to natural weathering | 111 |
| Figure 5.17 | Comparison of tensile strength after 6 months natural weathering   | 113 |
| Figure 5.18 | Comparison of elongation at break after 6 months natural weathering  | 114 |



|             |  |     |
|-------------|--|-----|
| Figure 5.19 | Comparison of tensile modulus after 6 months natural weathering  | 115 |
| Figure 5.20 | SEM morphology of RPP/PSP/PVOH composites at (a) 10 wt.% (b) 30 wt.% and (c) 40 wt.% of PSP loading after 6 months exposure to natural weathering  | 117 |
| Figure 5.21 | FTIR spectra of (a) unweathered RPP/PSP/PVOH composites with 10 wt.% PSP loading, (b) weathered RPP/PSP/PVOH composites with 10 wt.% PSP loading and (c) weathered RPP/PSP/PVOH composites with 40 wt.% PSP loading after 6 month natural weathering | 118 |
| Figure 5.22 | Carbonyl index of RPP/PSP and RPP/PSP/PVOH composites over a period of weathering for 6 months   | 120 |
| Figure 5.23 | Heating thermogram of modified composites before and after weathering  | 121 |
| Figure 5.24 | Cooling thermogram of modified composites before and after weathering  | 121 |
| Figure 6.1  | The processing torque of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites during the 12 min of mixing at different PSP loading   | 126 |
| Figure 6.2  | The stabilization torque of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at different PSP loading  | 127 |
| Figure 6.3  | Tensile strength of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at different PSP loading  | 128 |
| Figure 6.4  | Elongation at break of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at different PSP loading   | 129 |
| Figure 6.5  | Tensile modulus of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at different PSP loading   | 130 |
| Figure 6.6  | SEM micrographs of RPP/PSP composites at (a) 10 wt.% and (b) 40 wt.% PSP loading   | 132 |
| Figure 6.7  | SEM micrographs of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at (a) 10 wt.% and (b) 40 wt.% PSP loading   | 132 |
| Figure 6.8  | IR spectra of (a) RPP/PSP/H <sub>2</sub> O <sub>2</sub> and (b) RPP/PSP composites   | 133 |

|             |   |     |
|-------------|---|-----|
| Figure 6.9  | Water absorption over 30 days of RPP/PSP/H <sub>2</sub> O <sub>2</sub> at different PSP loading   | 135 |
| Figure 6.10 | Equilibrium water absorption of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites at 30 days   | 135 |
| Figure 6.11 | Heating thermogram of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites  | 136 |
| Figure 6.12 | Cooling thermogram of RPP/PSP and RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites  | 137 |
| Figure 6.13 | TG thermograms of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites  | 139 |
| Figure 6.14 | DTG thermograms of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites   | 139 |
| Figure 6.15 | Visual observation of treated composites at various PSP loading after 6 months exposure to natural weathering   | 141 |
| Figure 6.16 | Comparison of tensile strength after 6 months natural weathering  | 142 |
| Figure 6.17 | Comparison of elongation at break after 6 months natural weathering   | 144 |
| Figure 6.18 | Comparison of tensile modulus after 6 months natural weathering   | 145 |
| Figure 6.19 | SEM morphology of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites with (a) 10 wt.% (b) 30 wt.% and (c) 40 wt. % of PSP loading after exposure to natural weathering for 6 months   | 146 |
| Figure 6.20 | FTIR spectra of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites (a) unweathered with 10 wt.% PSP loading, (b) weathered with 10 wt.% PSP loading and (c) weathered with 40 wt.% PSP loading after 6 month natural weathering | 148 |
| Figure 6.21 | CI for unweathered and weathered RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites over a period of weathering for 6 months  | 149 |
| Figure 6.22 | Heating thermogram of treated composites before and after exposure to natural weathering  | 150 |
| Figure 6.23 | Cooling thermogram of treated composites before and after exposure to natural weathering  | 150 |

|             |   |     |
|-------------|---|-----|
| Figure 7.1  | Tensile strength of non-irradiated and irradiated RPP/PSP composites at different PSP loading                           | 154 |
| Figure 7.2  | Elongation at break of non-irradiated and irradiated RPP/PSP composites at different PSP loading                        | 156 |
| Figure 7.3  | Tensile modulus of non-irradiated and irradiated RPP/PSP composites at different PSP loading                            | 157 |
| Figure 7.4  | Tensile fractured surface of (a) 10 wt.%, (b) 20 wt.%, (c) 40 wt.% PSP loading of non-irradiated RPP/PSP composites     | 158 |
| Figure 7.5  | Tensile fractured surface of (a) 10 wt.%, (b) 20 wt.%, (c) 40 wt.% PSP loading of irradiated RPP/PSP composites         | 159 |
| Figure 7.6  | FTIR spectra of (a) non-irradiated and (b) irradiated RPP/PSP composites at 10 wt. % PSP loading and a zoom at C=O band | 161 |
| Figure 7.7  | Water absorption over 30 days of irradiated RPP/PSP composites at different filler loadings                             | 162 |
| Figure 7.8  | Equilibrium water absorption of non-irradiated and irradiated RPP/PSP composites at 30 days                             | 163 |
| Figure 7.9  | Heating thermogram of non-irradiated and irradiated RPP/PSP composites  | 165 |
| Figure 7.10 | Cooling thermogram of non-irradiated and irradiated RPP/PSP composites  | 165 |
| Figure 7.11 | TG thermograms of irradiated RPP/PSP composites   | 166 |
| Figure 7.12 | DTG thermograms of irradiated RPP/PSP composites  | 167 |
| Figure 7.13 | Comparison of tensile strength after 6 months natural weathering  | 169 |
| Figure 7.14 | Comparison of elongation at break after 6 months natural weathering   | 171 |
| Figure 7.15 | Comparison of tensile modulus after 6 months natural weathering   | 172 |

|             |   |     |
|-------------|---|-----|
| Figure 7.16 | SEM morphology of irradiated RPP/PSP composites with (a) 10 wt.% (b) 30 wt.% and (c) 40 wt. % of PSP loading after exposure to natural weathering for 6 months  | 174 |
| Figure 7.17 | FTIR spectra of RPP/PSP/H <sub>2</sub> O <sub>2</sub> composites (a) unweathered with 10 wt.% PSP loading, (b) weathered with 10 wt.% PSP loading and (c) weathered with 40 wt.% PSP loading after 6 month natural weathering | 175 |
| Figure 7.18 | CI for non-irradiated and irradiated composites over a period of weathering for 6 months  | 176 |
| Figure 7.19 | DSC heating thermogram of irradiated RPP/PSP composites after 6 months exposure to natural weathering   | 172 |
| Figure 7.20 | DSC cooling thermogram of irradiated RPP/PSP composites after 6 months exposure to natural weathering   | 178 |

## LIST OF ABBREVIATIONS

|       |   |
|-------|---|
| ASTM  | American Society for Testing and Materials  |
| CEN   | European Committee for Standardization      |
| CI    | Carbonyl Index                              |
| DSC   | Differential Scanning Calorimetry           |
| DTG   | Derivative Thermogravimetric                |
| EB    | Electron Beam                               |
| FESEM | Field Emission Scanning Electron Microscopy |
| FTIR  | Fourier Transform Infra Red                 |
| HDPE  | High Density Polyethylene                   |
| LDPE  | Low Density Polyethylene                    |
| LLDPE | Linear Low Density Polyethylene             |
| MSW   | Municipal Solid Waste                       |
| NaOH  | Sodium Hydroxide                            |
| PE    | Polyethylene                                |
| PEAA  | Polyethylene-co-Acrylic Acid                |
| PET   | Polyethylene Terephthalate                  |
| PLA   | Poly (lactic acid)                          |
| PMMA  | Poly(methyl methacrylate)                   |
| PP    | Polypropylene                               |
| PS    | Polystyrene                                 |
| PSP   | Peanut Shell Powder                         |
| PVC   | Poly(vinyl chloride)                        |
| PVOH  | Poly(vinyl alcohol)                         |

|     |                              |
|-----|------------------------------|
| RPP | Recycled Polypropylene       |
| SEM | Scanning Electron Microscopy |
| TG  | Thermogravimetric            |
| TGA | Thermogravimetric Analysis   |
| UV  | Ultraviolet                  |
| WA  | Water Absorption             |
| XRD | X-ray Diffraction            |

## LIST OF SYMBOLS

|                               |                              |
|-------------------------------|------------------------------|
| %                             | Percentage                   |
| $\Delta H_f$                  | Heat of fusion               |
| $\Delta H_m$                  | Melt enthalpy                |
| $^{\circ}\text{C}$            | Degree Celsius               |
| $^{\circ}\text{C}/\text{min}$ | Degree Celsius per minute    |
| cm                            | Centimetre                   |
| g                             | Gram                         |
| $\text{g}/\text{cm}^3$        | Gram per centimeter cubic    |
| GPa                           | GigaPascal                   |
| $\text{m}^2/\text{g}$         | Meter square per gram        |
| min                           | Minute                       |
| mm                            | Millimeter                   |
| mm/min                        | Millimeter per minute        |
| MPa                           | MegaPascal                   |
| mW                            | miliWatt                     |
| nm                            | Nanometer                    |
| phr                           | Parts per hundred            |
| rpm                           | Revolutions per minute       |
| s                             | Second                       |
| T                             | Temperature                  |
| $T_c$                         | Crystallization temperature  |
| $T_d$                         | Decomposition temperature    |
| $T_g$                         | Glass transition temperature |

|       |                         |
|-------|-------------------------|
| $T_m$ | Melting temperature     |
| w/w   | Weight to weight ratio  |
| wt. % | Weight percent          |
| $X_c$ | Degree of crystallinity |