An Experimental Study of Lignocellulosic (Oil Palm Residues) Pretreatments for Cellulose Extraction

Tanakorn Wongwuttanasatian*, Amnat Suksri, and Kittichai Jookjantra

Abstract— *This research aimed to investigate the effectiveness of the pretreatments for cellulose extraction of oil palm residues. Steam explosion method and acid or alkaline digestion based on detergent analysis method were the pretreatments used in this research. Four types of oil palm residues were considered: oil palm seed meal, oil palm meal, oil palm leaf, and oil palm trunk. The effectiveness of the two pretreatments was determined by measuring the amounts of percent cellulose extracted from all four types of oil palm residues. The cases steam explosion pretreatment provided higher percent cellulose than the acid or alkaline digestion cases did for all cases. Oil palm seed meal showed the highest percent cellulose extracted compared to those of the other three oil palm residues for both pretreatments.*

Keywords— **Oil palm, residues, steam explosion, detergent analysis.**

1. INTRODUCTION

Ethanol is an alternative fuel that has gained a lot of attention due to its cleaner energy compared to gasoline. In Thailand, ethanol production is mainly from sugar (cane and molasses) and starches (cassava, rice, and maize) [1]. The Ministry of Energy, Thailand had supported the ethanol production during 2008 to 2011 by targeting the annual production capacity of 3 million liters. However, the current ethanol production could only reach 2.95 million liters/year (1.76 million liters of molasses/year and 1.19 million liters of cassava/year) which is not enough capacity [2]. As a result, there is still a shortage of raw materials in the production of ethanol. The conversion of food crops to biomass energy crops also provides a risk to food security. One of the potential raw materials other than food is lignocellulosic materials [3]. Oil palm residues are lignocelluloses and usually in a form of waste from oil palm or biodiesel industry. Over the past several years, Thai government has encouraged farmers in the east and south of Thailand to cultivate oil palm [4]. In addition, oil palm trees are usually cut down after 25 years due to their inability to yield palm oil anymore, causing a lot of oil palm waste. Moreover, oil palm waste is normally disposed or incinerated, which offers a great threat to the environment. Apart from the abundance of oil palm residues, the preliminary study showed that dry oil palm had a proportion of cellulose up to 37.14 % which has a high potential to be a source of ethanol production [5].

In order to convert oil palm cellulose to ethanol, the structure of lignocelluloses must be digested by using pretreatment [6]. Umikalsom et al [7] examined the pretreatment of empty fruit bunch by soaking it in nitric acid (HNO_3) at a concentration of 0.5% by volume for 4 hours and then boiling it at 121 °C at a pressure of 15 lb for 5 minutes by using the steam sterilizer. The researchers found that the pretreatment provided 62.9±0.90% by weight of cellulose based on the empty fruit bunch that had 50.4±1.20% by weight of cellulose. Rashid et al [8] found that the pretreatment of oil palm stems by using sodium hydroxide at a concentration of 3% at 100 °C for 2 hours would result in an increase of 24.42% of cellulose. As a result, if oil palm residues, particularly oil palm trunk, are used as a renewable energy source to replace gasoline, this will reduce the shortage of raw materials in the production of ethanol, generate income to the oil palm farmers, and also enhance the country's competitiveness of renewable energy.

This paper aimed to study the effectiveness of two pretreatment methods: (1) steam explosion and (2) acid or alkaline digestion based on detergent analysis on four types of oil palm residues (oil palm seed meal, oil palm meal, oil palm leaf, and oil palm trunk). The amounts of cellulose of oil palm residues extracted from the two pretreatment methods were measured and compared to determine the effectiveness of each method.

2. EXPERIMENTAL METHODS

2.1 Materials preparation.

Four types of oil palm residues were considered in this paper: (1) oil palm trunk, (2) oil palm leaf, (3) oil palm meal, and (4) oil palm seed meal as shown in Fig. 1. These four oil palm residues were grounded and cut to have 0.20 mm to 2 mm in width and 10 mm to 20 mm in length. These oil palm residues were controlled to have humidity less than 100% by sun drying or baking. The dried oil palm residues were then chemically extracted to determine the percent amounts of cellulose, lignin, moisture, and ash.

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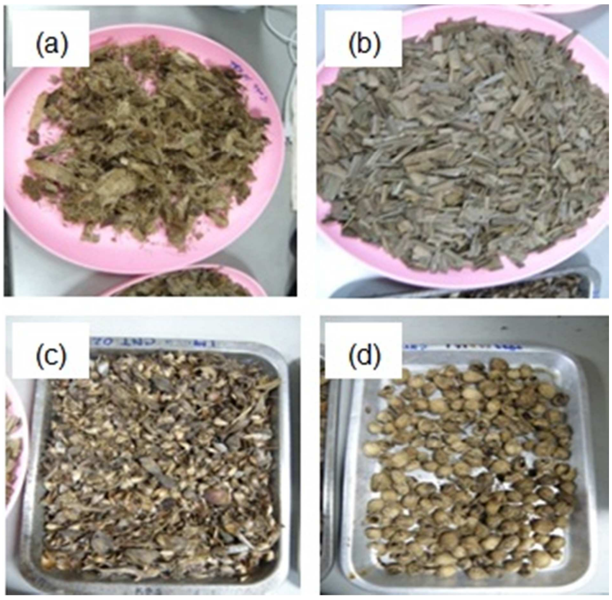

Fig. 1 Oil palm residues as the raw materials. (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed meal.

Fig 2. The oil palm residues after soaking in 0.08% diluted sulfuric acid for 8 hours (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed meal.

Fig 3. The steam explosion machine.

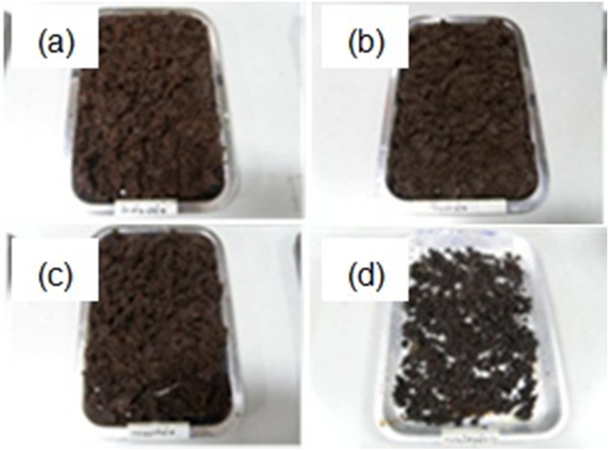

Fig 4. Digested residues after washed with hot water at 80 °C for 30 minutes (a) Oil palm trunk. (b) Oil palm leaf. (c) Oil palm meal. (d) Oil palm seed.

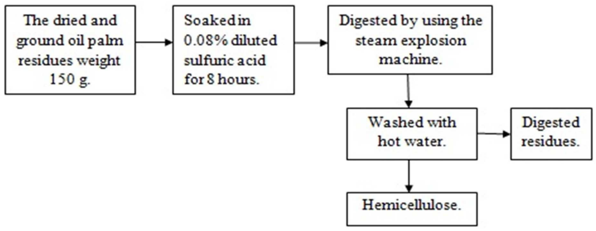

Fig 5. Procedure of digested residues with the steam explosion method.

2.2 Steam explosion pretreatment

The pretreatment by using steam explosion carried out in this paper was based on the work of Punsovon et al [5]. To begin the pretreatment, 150 g of the dried and ground oil palm residues obtained from the materials preparation (approximately 1 mm in width) was soaked in 0.08% diluted sulfuric acid for 8 hours. The Fig. 2 showed the oil palm residues after soaking. Then, the structure of these residues was digested by using the steam explosion machine (shown in Fig. 3) at 203 °C for 5 minutes. The digested residues were washed with hot water at 80 °C for 30 minutes to remove hemicelluloses as shown in Fig. 4. The ratio of digested residues per hot water was 1:10 (in 1 L of hot water). Then, the digested residues were dried and chemically extracted to determine the chemical compositions in accordance with TAPPI T203 om-88 [9]. The procedure of steam explosion pretreatment is illustrated in Fig. 5.

2.3. Acid or alkaline digestion based on detergent analysis pretreatment

The pretreatment by using acid or alkaline digestion based on detergent analysis carried out in this paper was based on the work of Goering et al [10] to begin the pretreatment, 150 g of the dried and ground oil palm residues obtained from the materials preparation (approximately 1 mm in width) were boiled with a neutral solution. Fig. 6 showed the procedure of wall cells analysis with detergents method. Then, Neutral Detergent Fiber (NDF) was analyzed to obtain percent

NDF as in Fig. 7. Afterward, the extracted NDF solution was boiled with an acid solution. Then, Acid Detergent Fiber (ADF) was analyzed to obtain percent ADF as in Fig. 8. Next, the extracted ADF solution was digested by using sulfuric acid (H_2SO_4) with a concentration of 72%. Then, the Acid Detergent Lignin (ADL) was analyzed to obtain percent ADL. Finally, the percent amount of cellulose was calculated by:

$$\textit{Percent cellulose} = (\textit{weight of ADF} - \textit{weight of ADL}) / \textit{weight of dried oil palm residues.} \quad (1)$$

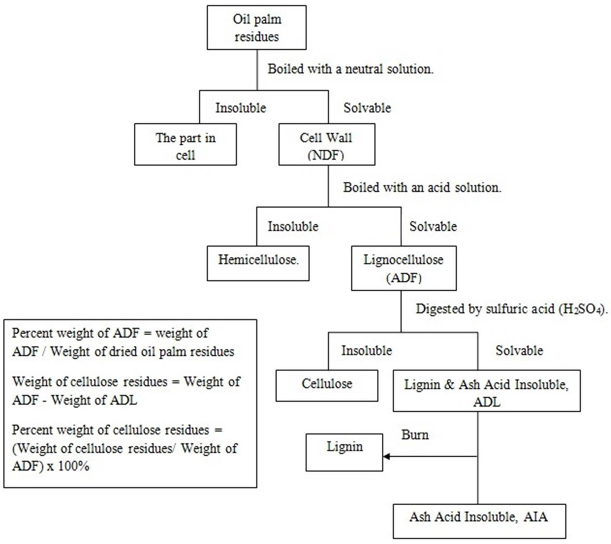

Fig. 6. Procedure of wall cells analysis with detergents method.

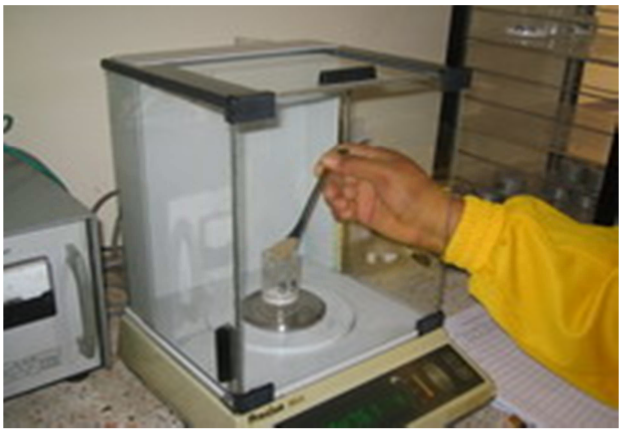

Fig 7. Analysis of % NDF as NDF testing method.

3. RESULTS

3.1 Chemical extraction of oil palm residues.

According to Table 1, the highest to lowest amounts of percent cellulose of oil palm residues prior to being pretreated were from oil palm trunk (29.98%), oil palm leaf (28.91%), oil palm meal (28.22%), and oil palm seed meal (28.15%), respectively.

Fig 8. Analysis of % ADF as ADF testing method.

Table 1. Results of chemical extraction of oil palm residues

Types of oil palm residues	Percent weight (%)			
	Cellulose	Lignin	Moisture	Ash
Oil palm seed meal	28.15	36.49	11.40±0.06	8.80±0.18
Oil palm meal	28.22	33.23	12.52±0.13	7.72±0.28
Oil palm leaf	28.91	45.22	14.57±0.27	10.62±0.16
Oil palm trunk	29.98	33.43	10.78±0.09	8.32±0.28

3.2 Results of steam explosion pretreatment.

According to Table 2, the highest to lowest amounts of percent cellulose of oil palm residues after the steam explosion pretreatment were from oil palm seed meal (34.72%), oil palm trunk (19.55%), oil palm meal (18.96%), and oil palm leaf (28.91%), respectively. Even though oil palm seed meal provided the highest percent cellulose, its structure was the strongest, which was difficult for digestion.

Table 2. The differences of percent cellulose before and after the steam explosion pretreatment

Types of oil palm residues	Before pretreatment	After pretreatment	Difference of percent cellulose before and after pretreatment
	Percent cellulose (%)	Percent cellulose (%)	
Oil palm seed meal	28.15	34.72	6.57% increase
Oil palm meal	28.22	18.96	9.26% decrease
Oil palm leaf	28.91	13.35	15.56% decrease
Oil palm trunk	29.98	19.55	10.43% decrease

3.3 Results of acid or alkaline digestion based on detergent analysis pretreatment

According to Table 3, the highest to lowest amounts of percent cellulose after the acid or alkaline digestion based on detergent analysis pretreatment were from oil palm seed meal (28.17%), oil palm meal (16.20%), oil palm trunk (15.96%), and oil palm leaf (12.75%), respectively. Similar to the results obtained from the steam explosion pretreatment, oil palm seed meal provided the highest percent cellulose but its structure was the strongest, which was difficult for digestion.

Table 3. The differences of percent cellulose before and after the acid or alkaline digestion based on detergent analysis pretreatment

Types of oil palm residues	Before pretreatment	After pretreatment	Difference of percent cellulose before and after pretreatment
	Percent cellulose (%)	Percent cellulose (%)	
Oil palm seed meal	28.15	28.17	0.02% increase
Oil palm meal	28.22	16.20	12.02% decrease
Oil palm leaf	28.91	12.75	16.16% decrease
Oil palm trunk	29.98	15.96	14.02% decrease

4. DISCUSSION AND CONCLUSION

This paper investigated the effectiveness of the two pretreatment methods: (1) steam explosion, and (2) acid or alkaline digestion based on detergent analysis. The effectiveness was determined by measuring the percent cellulose of four types of oil palm residues: (1) oil palm seed meal, (2) oil palm meal, (3) oil palm leaf, and (4) oil palm trunk before and after the pretreatments.

The results showed that most of the amounts of percent cellulose (oil palm meal, oil palm leaf, and oil palm trunk) were decreased after the pretreatments. This was due to the fact that the operating conditions for cellulose extraction used in each pretreatment were not optimized. However, the pretreatments of oil palm seed meal provided an increase in percent cellulose, which was due to the strength of oil palm seed meal and the effectiveness of hemicellulose removal. The steam explosion pretreatment provided higher amounts of percent cellulose than those of using the acid or alkaline digestion based on detergent analysis pretreatment. This was mainly due to the more effective hemicelluloses removal of the steam explosion pretreatment.

The authors also found that the steam explosion pretreatment should be used for strong oil palm residues and the acid or alkaline digestion based on detergent analysis pretreatment should be used for soft oil palm residues. Nevertheless, the operating conditions for cellulose digestion of each pretreatment should be optimized for each type of oil palm residue.

ACKNOWLEDGMENTS

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NOMENCLATURE

ADF	The Acid Detergent Fiber
ADL	The Acid Detergent Lignin
AIA	The Ash Acid Insoluble
NDF	The Neutral Detergent Fiber

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Application of Heat Insulation Solar Glass for Glass Buildings

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Abstract— *To enhance electrical energy production and improve heat insulation of photovoltaic modules (original solar glass module), a simple method for installation and generation of heat insulation solar glass (HISG) modules from traditional transparent PV modules (original solar glass modules) using heat insulation materials, improving functions such as power generation, heat insulation, energy saving and greenhouse gas reducing. Interest in photovoltaics (PV) integration into buildings, as well as heat insulation solar glass (HISG) be used as curtain walls on the buildings has been developed, where the HISG curtain walls play the role of building exterior components as an integral part of buildings as well as of producing electricity and providing functions such as heat insulation and self-cleaning. Two experimental houses used normal glass and HISG as curtain walls on the Ordinary house and the HISG house were constructed in this study. Results show that the illuminative penetration on HISG curtain was quietly high with efficiency of 32%, block UV-rays to 100%, low solar radiation 40% as compared to normal glass curtain wall (~97%), greatly enhanced indoor lighting ~29.4% and high heat insulation efficiency ~28.2% as compared to normal glass curtain wall on the Ordinary house. In addition, the energy-saving efficiency of the HISG house for heating and cooling were greatly improved respective to ~40% and 48% for comparisons to the Ordinary house, and the power generation of HISG curtain wall on the HISG house was achieved 2.63 kWh of electricity per day. Our work offers a low-cost route to the application of HISG modules able to be used for monitoring progression of the greenhouse gas reduction, as well as evaluating their energy efficiency on buildings in the green buildings at the current and future.*

Keywords— **Heat insulation solar glass (HISG), glass, HISG curtain wall, power generation, heat insulation, energy saving, HISG house, Ordinary house.**

1. INTRODUCTION

In recent years, the energy crisis has prompted many countries on the world more interesting to research renewable energy because of that can be significantly replaced traditional energy sources. Thus, energy saving has been interested and attracted by many scientists as an important and urgent issue due to soaring energy price and gradual depletion of fossil fuels resources. Most of the renewable energy resources currently are available, in which solar energy is one of the most abundant, inexhaustible and clean sources [1], [2]. Therefore, photovoltaics is a truly convenient methods of the electrical energy production on site, directly from the sun, without concern for energy supply or environmental harm, as well as significantly reduced amount of CO_2 gas emission into the natural environment (e.g., greatly reduced greenhouse gas on buildings) in recent years [3], [4].

As we known, the building integrated photovoltaics (BIPVs) are photovoltaic materials, which are able to use to replace conventional building materials in parts of the envelopes or roofs in construction, as a functional part of the building structure or architecturally integrated into the building's design. Moreover, BIPVs can act as shading devices and a semi-transparent material of fenestration. Whereas, other semi-transparent modules can be used in facades or ceilings by using those glass modules to generate various visual effects [5]. Besides, the combination between original solar module and other glass types can be used for many goals (e.g., re-protection, low-e insulation, sun protection or bullet-proof) application in the buildings [6].

Nowadays, the modern buildings are significantly high raised and more energy consuming (or increased power energy need). However, it was required to provide large amount of power energy need and significant decreased emission of CO_2 gas in the environment life, as well as how to design and construct buildings to zero energy, which was not a small challenge for the design of buildings [7], [8]. Thus, related studies have focused on combination methods, system improvements and developments of photovoltaic (PV) cell materials recently. A more clearly comprehensive approach, as

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well as feasibility study, is needed to explore with wider areas how to use existing PV cells to reduce annual energy consumed by high-rise buildings, as well as to conduct and energy saving for feasibility studies in the green building [9]. Thus, to install BIPV modules on buildings suggested the consideration to other problems, first, to avoid energy loss as well as waste during the stand-by mode of the power system or coming from windows, double facades was required to use or a grid-connected system should be used for saving or reducing waste of energy consumption [10]-[12]. Moreover, it was also noted that cooling load could be better than power generated from the PV module system if the system is used as solar shading device [13]-[15], [8], [11]. Therefore, energy consumed by air conditioners or heaters can be significantly reduced, and the building becomes self-sufficient in terms of power demands.

To overcome the challenges about the increasing of power generation from BIPV system used in the green building and to reduce energy consumption of the buildings as well significantly greenhouse gas reducing in buildings. In this study, heat insulation solar glass (HISG) module was applied as curtain walls in the experimental house in Taiwan. The HISG module has been developed successfully by Young et.al. [16], which possessed multiple functions including power generation enhancement, great heat insulation, high energy saving efficiency, good self- cleaning capability and significantly greenhouse gas reduction on buildings.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1 Methods

The structure of PV module (Tandem type) and HISG module were shown in details as Fig. 1. In this work, HISG module was applied as glass curtain wall on the experimental house, which was fabricated and described more details – see the previously report [16].

Herein, we have used normal glass and HISG as curtain walls installed on the Ordinary house and the HISG house, respectively. For comparisons about the illuminative penetration, UV penetration, solar radiation, indoor lighting ability, heat insulation (temperature flow test), energy-saving efficiency (the energy was consumed for the heating and cooling) between the Ordinary house (normal glass) and the HISG house (e.g, midi logger GL 220, T340, etc…), and the power generation measurement of the HISG house was performed by using equipment of SIV-1000M for the investigation.

2.2 Materials

Heater and air conditioner devices were used for testing of saving energy consumption (i.e, SAMPO HX-YB12P: 1250W, and TECO LT63FP1-41003), and other materials such as heat insulation film, air, alcohol, aceton, nano photocatalyst were purchased from Acros. All solutions were prepared using deionized water from a MilliQ system.

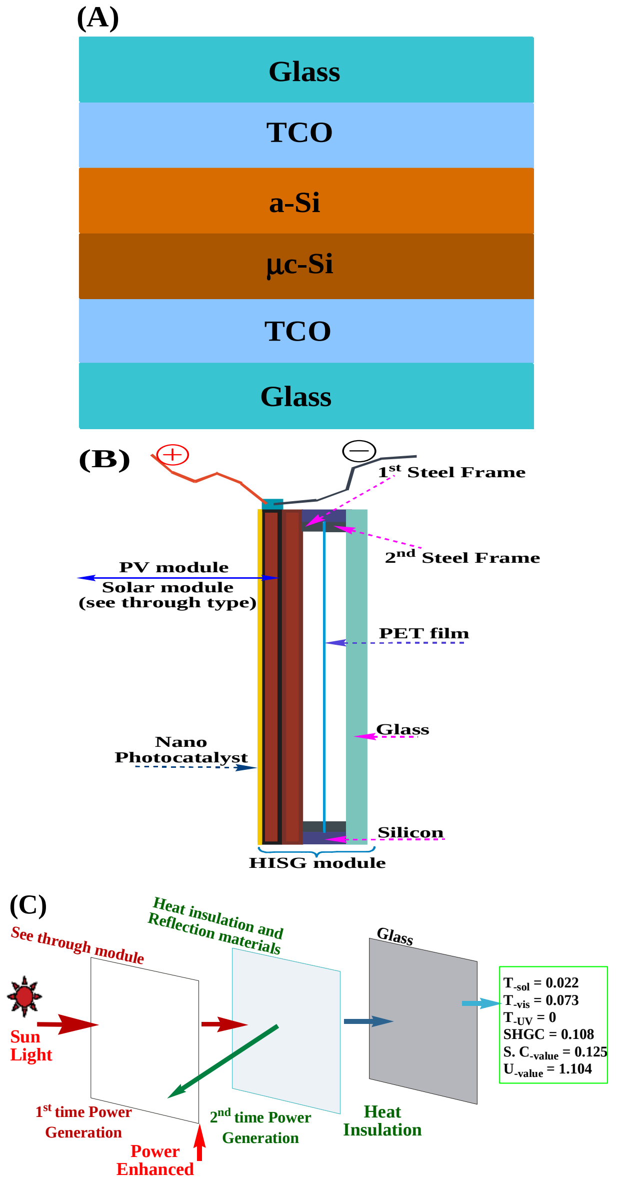


Fig. 1. Structures of (A) original PV module and (B) HISG module (thickness ~28 mm), and (C) Scheme about function theory of HISG (T sol is the solar transmittance, T vis is the visible light transmittance, T UV is the UV transmittance, SHGC is the solar heat gain coefficient, S.C. is the shading coefficient, and U value is the thermal transmittance of HISG) [16].

Table 1. Detail parameters of glazing curtain wall types

Items	Normal glass	HISG
Thickness (mm)	12	28
Visible light	87%	7.15%
U value (W/m^2K)	5.97	1.65
K value (W/mK)	1.05	0.032
Shading coefficient (SC)	0.87	0.144
Houses' size (m)	Length: 3.04; Width: 2.51; Height: 3.17	
Fenestration area (m^2)	Vertical: 24.64; Roof surface: 6.16	
Dimension (mm)	1400×1100	

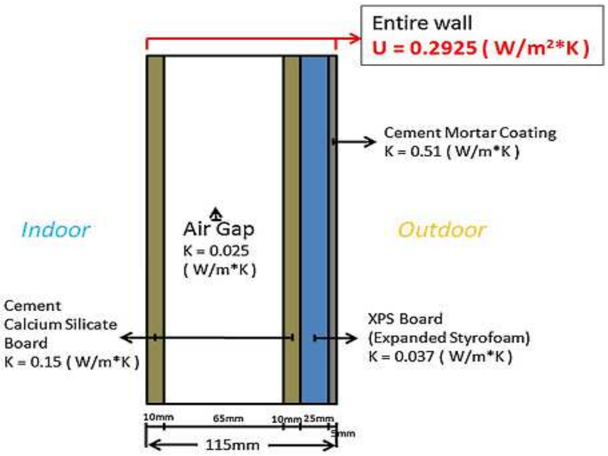


Fig. 2. Thickness and thermal conductivity of all elements of the external envelope of the experimental houses.

3. RESULTS AND DISCUSSION

3.1 Illuminative penetration performance of normal glass and HISG curtain walls on buildings

As shown in Fig. 3, the indoor illumination of the HISG house using HISG curtain wall is 2960 Lux much lower than that of the Ordinary house using normal glass curtain wall to 40087 Lux. In addition, the effective light penetration of normal glass and HISG curtain walls on the houses are estimated about 95% and 32% as compared to outside skylight, respectively. Because, the visible light transmittance of HISG is only 7.15%, whereas the light transmittance of normal glass is being to 87% for contrasting.

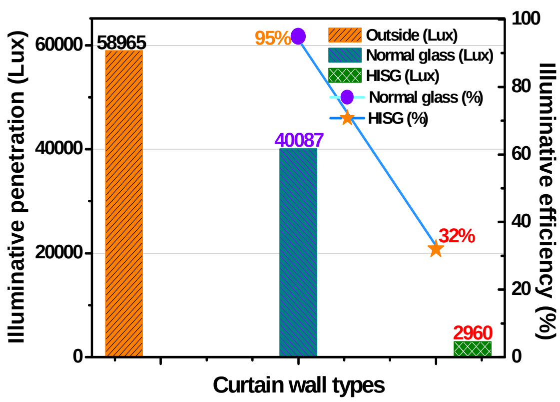


Fig. 3. Intensity and efficiency of illuminative penetration on Normal glass and HISG curtain walls for comparison to the outside skylight.

3.2 Testing of UV penetration on Normal glass and HISG curtain walls

UV penetration performance on the experimental houses was directly inside conducted at the middle point of the houses from 9:00 A.M. to 6:00 P.M. – see Fig. 4. The outdoor ultraviolet value is 5080 (uW/cm^2), and in the Ordinary house using normal glass curtain wall about 1231 (uW/cm^2), while that value in the HISG house using HISG curtain wall dropped to 0 (uW/cm^2). Moreover, the efficiency of UV isolation on normal glass and HISG curtain walls are calculated ~76%, and 100%, respectively. Thus, UV isolation of HISG curtain wall used is much better than that of normal glass curtain wall on the buildings. This isolation achieved because of air layers (with thickness ~12 mm, there are very low UV and thermal transmittance capacities) packaged with PV module to form HISG module. It indicated that the UV isolation on HISG curtain wall is excellent and achieved a 100% UV-blocking rate, completely halting the penetration or transmission of UV light and reducing harm to skin and furniture.

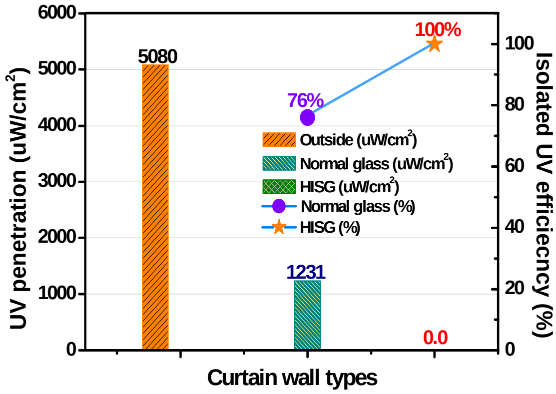


Fig. 4. Intensity and isolated efficiency of UV penetration on Normal glass and HISG curtain walls for comparison to the outside light.

3.3 Testing of solar radiation on Normal glass and HISG curtain walls

The anti-radiant solar efficiency was also performed on normal glass and HISG curtain walls on the experimental houses in this observation. As shown in Fig. 5, the intensity of outdoor solar radiation is measured to 1103 (W/m^2), that intensity on normal glass curtain wall of inside the Ordinary house dropped to 658 (W/m^2), while on HISG curtain wall of inside the HISG house that value is very low only 28.5 (W/m^2). And the effective isolation of solar radiation is also calculated about 40 and 97% for the using of normal glass and HISG curtain walls in the houses, respectively – see Fig. 5.

It demonstrated that radiant heat penetration of HISG curtain wall was significantly lower and its isolated efficiency achieved to 95% as compared to that of normal glass curtain wall and outdoor solar radiation. Thus, we can use HISG as curtain walls, as well as BIPV curtain wall for the replace of normal glass curtain wall on buildings due to the isolated efficiency of radiant heat penetration into the room very high, which can significantly reduce greenhouse gas and inside ambient temperature, and greatly saved energy consumption for heating and cooling of devices inside the houses.

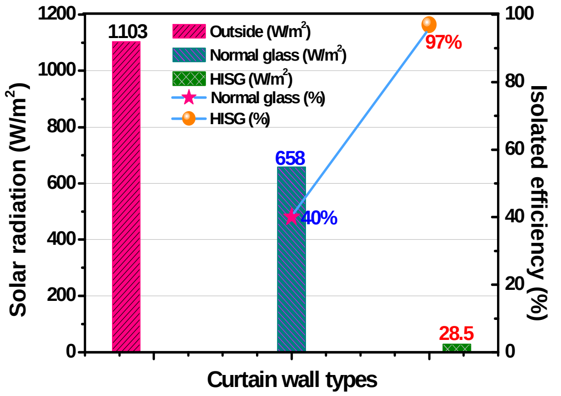


Fig. 5. Intensity and isolated efficiency of solar radiation on Normal glass and HISG curtain walls.

3.4 Indoor lighting measurement of using Normal glass and HISG curtain walls on the experimental houses

Results are shown in Fig. 6, the indoor lighting efficiency of a light 40W at all positions of the HISG house using HISG curtain is much higher than that of the Ordinary house using normal glass curtain for lights 40W used. This efficiency is obtained ~24.9% for the indoor lighting of the HISG house – see Fig. 6. Consequently, the HISG house can be significantly improved and enhanced indoor lighting at night, which is much better than that of the Ordinary house – see Fig. 7. That may be due to the structure of HISG can be conversed and generated power energy from solar energy with high efficiency, which is a sandwich structure containing PV module and a metal reflection film, leading to increased light reflection and significantly enhanced lighting for devices used inside the HISG house. Whereas normal glass curtain of the Ordinary house has no light reflection film layer, the light source cause damage from outside will be easily penetrated into the house and be decreased lighting of devices used inside the house due to the light diffusion to outside environment more, leading to increase energy expense much more.

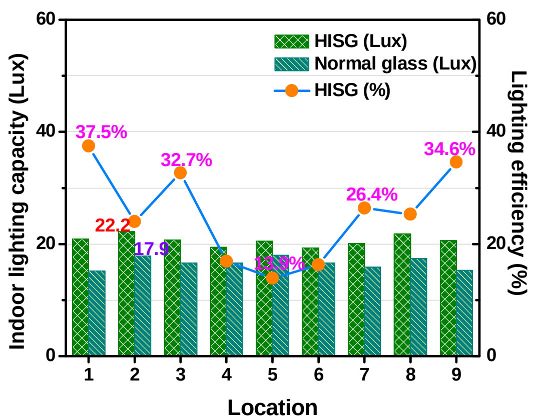


Fig. 6. Intensity and efficiency of indoor lighting of using normal glass and HISG curtain walls on the Ordinary house and the HISG house at various positions, respectively.

Fig. 7. Photograph of inside lighting on (A) the HISG house and (B) the Ordinary house at night, respectively.

3.5 Study of the heat insulation of the experimental houses

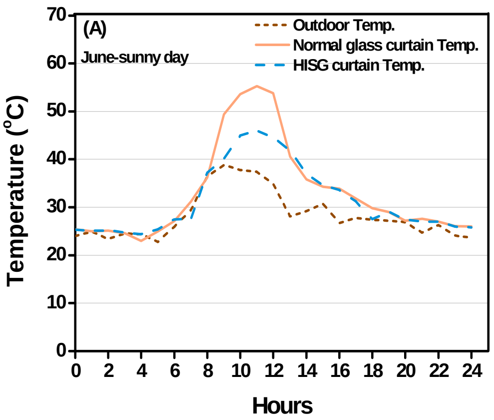
Thermometers were installed in the two houses. The effect of outdoor environment related to the indoor ambient temperature were determined during spring (in March) and summer (in June) seasons from 0:00 A.M. to 12:00 P.M. for comparisons between indoor temperature of the Ordinary house and the HISG house as shown in Fig. 8.

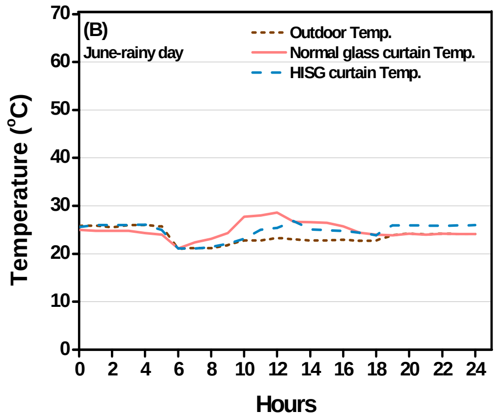
In summer, the outdoor ambient temperature reaches the maximum temperature of 38.8^{o}C at 10:00 A.M., which gradually increases from 36.5^{o}C at 8:00 A.M. to 37.4 and 34.8^{o}C at 11:00-12:00 A.M. and gradually decreases from 1:00-12:00 P.M. in sunny day. As shown in Fig. 8(A), the outdoor temperature rapidly increases from 7:00–12:00 A.M. and gradually decreases from 1:00-12:00 P.M.. Fig. 8(A) also shows a high temperature (~53-54.6^{o}C) in the Ordinary house using normal glass curtain wall from 10:00-12:00 A.M. due to direct exposure to solar radiation, thermal conduction and sealing, leading to interior heat accumulation and increasing temperature inside the house. Whereas, the indoor temperature of the HISG house using HISG curtain wall reaches the maximum value 44.7^{o}C at the same time (11:00 A.M.), which is lower than that of the Ordinary house with difference of 9.9^{o}C. This difference is due to the HISG curtain wall has good heat insulation, low thermal transmission and penetration of solar radiation, achieving to greatly themal insulation and reducing heat accumulation inside the house significantly. The indoor temperatures of the Ordinary house and the HISG house are approximately to the outdoor ambient temperature, when the outdoor temperature gradually decreases and not significantly change from 7:00–12:00 P.M. – see Fig. 8(A).

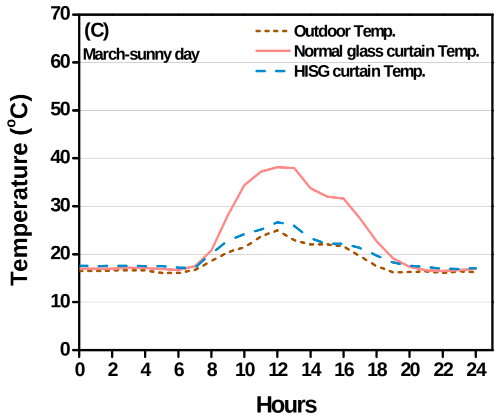
In rainy day, the outdoor temperature plunged from 6:00 A.M. to 6:00 P.M. The indoor temperature of normal glass curtain on the Ordinary house is quite sensitive to the effect of the external environment, which gradually decreases from 12:00 A.M. to 3:00 P.M. – see Fig. 8(B). Since when the rain, the temperature diffusion to outside environment of normal glass curtain was fast due to the good heat transmittance (~60%), quick heat absorption and low heat maintenance of normal glass curtain on the Ordinary house. The HISG curtain is good heat insulation and relatively less affected by outdoor factors. The reaction temperature of HISG curtain is slow, low heat conduction and after the rain around 1:00 P.M. the indoor temperature of HISG curtain in the HISG house is not significantly decrease due to the cooling of HISG curtain is slow with lowly thermal transmittance (~2.6%) and highly thermal maintenance. Thus, the indoor ambient temperature of the HISG house is not changed and still keep at ~26^{o}C, whereas the outdoor and indoor ambient temperature of the Ordinary house ~23^{o}C from 6:00-12:00 P.M. as shown in Fig. 8(B). It indicates that the heat insulation of HISG curtain in the HISG house is much better than that of normal glass curtain in the Ordinary house. Because the indoor temperature of the HISG house is always much lower than that of the Ordinary house from 6:00 A.M. to 6:00 P.M. – see Fig. 8(A, B).

In spring, the maximum indoor temperature of the Ordinary house reached 38.2^{o}C; whereas the outdoor and indoor temperature of the HISG house were respective 25^o and 26.7^{o}C at 12:00 A.M. as shown in Fig. 8(C). Results show that the outdoor and indoor temperature of the HISG house is equivalent, which is lower than that of the Ordinary house reached 11.5^{o}C. Sunning duration is 12 h, the incidence angle of the sun rays and solar radiation crossing glazing remains significant on the normal glass curtain, leading to its indoor temperature being much higher than that on the HISG curtain.

During rainy day, the indoor temperature of the Ordinary house and the HISG house is not significant difference (only ~1.2^{o}C at 12:00 A.M.) due to has no sunlight – see Fig. 8(D). Thus, the temperature change between them occurred so small and not significant. The average value of sunlight per hour less than 50 W/m^2 at 0:00–7:00 A.M. and 7:00–12:00 P.M., the outdoor and indoor temperature of the Ordinary house and the HISG house is almost the same as shown in Fig. 8(D). The main reasons may be due to the solar radiation very low, convection and movement between free air molecules low, leading to difficult controlling temperature inside the houses.







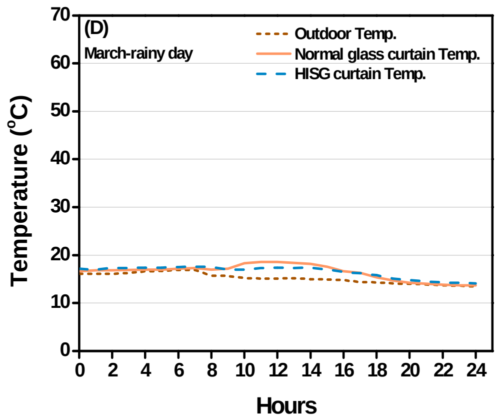


Fig. 8. Hourly variations of indoor and outdoor temperature curves of the HISG house and Ordinary house during summer with (A) sunny day and (B) rainy day; and spring with (C) sunny day and (D) rainy day, respectively.

3.6 The energy-saving investigation of glass curtain wall in the experimental houses

Herein, we have built two 2.51 m (l) × 3.04 m (w) × 3.17 m (h) houses, which were named the HISG House and the Ordinary House (normal glass house) in Taipei of Taiwan for comparison – see Fig. 9.

Fig. 9. Outside appearance of experimental houses: (A) Oridinary House (using Normal glass) and (B) Heat Insulation Solar House (using HISG).

3.6.1 Experiment relating to the energy consumption of air conditioners

Electricity meters (Watt-hour) and air conditioners were installed in two houses to determine the effects of two glass types difference in the energy consumption of air conditioner during the summer as shown in Table 2.

Herein, the air conditioners were set up at 26°C when the outdoor temperature at 35°C, from 6:00 A.M. to 6:00 P.M.. Our experimental results show the air conditioner in the Ordinary House consumed 2.5 kWh of electricity, while in the HISG House consumed only 1.3 kWh. This is estimated about 48% air conditioner energy consumption reduction for HISG compared to the single-layer tempered glass (the Ordinary House). This reduction is very significantly for the using of HISG module in the buildings or Houses due to the extremely small shading coefficient of HISG (nano photocatalyst coated on the HISG module's surface) and high heat radiation anti-reflection from sunlight, as well as reducing large amount of energy consumption because of a good heat insulation layer of HISG, which shown and contributed to excellent heat insulation effects and prevented solar radiation heat from entering the house. Moreover, the U-value of HISG is significantly low, cold air could not easily leave or disperse from the indoor environment, as well as not much lost from electrical energy consumption for the surrounding environment. Thus, the energy-saving efficiency was successful achieved because a large amount of electrical energy consumption from the activation of air-conditioner compressor frequency was significantly reduced.

Table 2. Experimental results about the energy consumption of air conditioner

Item	HISG House	Oridinary House
Time duration	6:00 A.M. – 6:00 P.M.	
Outdoor temperature (°C)	35	
Setting temperature (°C)	26	
Air conditioner consumption (kWh)	1.3	2.5
Energy saving (%)	42.31	–

3.6.2 Experiment for the energy consumption of heaters

Electricity meters (Watt-hour) and heaters were installed in two houses to observe the effects of two glass types in the energy consumption of heaters during the, as shown in Table 3.

In this work, the heaters were set up to 20°C when the outdoor temperature about 14°C, from 6:00 P.M. to 6:00 A.M.. As shown in Table 3, the heater of the Ordinary House consumed 1.5 kWh electrical energy, whereas the HISG House just consumed 0.9 kWh. This result shows a 40% reduction in the energy consumption of heaters for the HISG House as compared to the single-layer tempered glass. This reduction may be due to the HISG has a significantly low U-value, which prevented and decreased expense of hot air from diffusing out of the indoor environment through windows. Therefore, the effective energy-saving was significantly achieved and improved due to the excellent heat retention or good maintain functions of HISG.

Table 3. Experimental results for the heater's energy consumption

Item	HISG House	Oridinary House
Time duration	6:00 P.M. – 6:00 A.M.	
Outdoor temperature (°C)	14	
Setting temperature (°C)	20	
Heater consumption (kWh)	0.9	1.5
Energy saving (%)	40	–

3.7. Power generation performance of the HISG house

The power generation measurement of the HISG house was conducted through practical examinations. HISG modules were installed on all facades of East, South, West, North and Top (Roof) of the HISG house for practical tests were also performed as results shown in Table 4.

HISG modules installed on the roof (Top) were obtained 1.19 kWh of electricity. And HISG modules installed on East, South, West, and North facades as curtain walls of the house were measured to 1.44 kWh of electricity. Thus, the power generation on the HISG house was obtained total 2.63 kWh of electricity per day. For comparison to the Ordinary house, the HISG house can added value of glass power generation due to the HISG integrated renewable solar energy into the building to produce additional power. Consequently, HISG can replace tempered glass (normal glass) in buildings, as new sustainable energy resources, which can significantly reduce greenhouse gas and gradually energy approximately to the zero in the buildings.

Table 4. Results of power generation output on HISG curtain wall by HISG house per day

All facades of the house	East	South	West	North	Top (Roof)	Total power output
Power generating capacity (kWh)	0.45	0.34	0.38	0.27	1.19	2.63
Efficiency (%)	17.1	12.9	14.4	10.3	45.3	100

4. CONCLUSION

HISG curtain wall was successfully applied on the experimental house in Taiwan, which was also widely developed for applying on buildings, as well as the roof of public transport systems. Because HISG was installed for buildings as glass curtain walls, its good self-cleaning capability keeps the module surface clean, leading to reducing the cost required for surface washing. Moreover, HISG has good many functions and properties such as the illuminative penetration quietly high with efficiency of 32%, with 100% UV-blocking rate, low solar radiation 40% as compared to normal glass curtain wall (~97%), greatly enhanced indoor lighting efficiency about 29.4% compared to normal glass curtain wall, highly effective heat insulation due to the indoor temperature of the HISG house was lower than that of the Ordinary house reached 8.9-11^{o}C. In addition, the energy-saving efficiency of the HISG house for heating and cooling were greatly improved to ~40% and 48%, respectively for comparisons to the Ordinary house. Furthermore, HISG curtain wall on the HISG house significantly enhanced and maintained the power generation efficiency and obtained to 2.63 kWh of electricity per day. The resulting increased electrical energy production, highly heat insulation, significantly greenhouse gas reducing, and greatly enhanced energy-saving leads to potential applications in buildings (e.g, Roofing, Skylight – canopies, Curtainwalls – vertical glass, offices, etc…). Consequently, they can be used and applied in the green buildings to significantly greenhouse gas reducing and gradually suitable trend to the zero energy building in future.

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