energies

MDPI

Article

All-Polyamide Composite Coated-Fabric as an Alternative Material of Construction for Textile-Bioreactors (TBRs)

Mostafa Jabbari *, Osagie A. Osadolor, Ramkumar B. Nair and Mohammad J. Taherzadeh

Swedish Centre for Resource Recovery, University of Borås, SE-50190 Borås, Sweden; alex.osagie@hb.se (O.A.O.); Ramkumar.nair@hb.se (R.B.N.); mohammad.taherzadeh@hb.se (M.J.T.)

* Correspondence: mostafa.jabbari@hb.se; Tel.: +46-33-4354-636; Fax: +46-33-4354-003

Received: 15 October 2017; Accepted: 14 November 2017; Published: 21 November 2017

Abstract: All-polyamide composite coated-fabric (APCCF) was used as an alternative material for the construction of textile-bioreactors (TBRs), which are prepared as a replacement of the traditional stainless steel bioreactors (SSBRs) or concrete-based bioreactors. The material characteristics, as well as the fermentation process performance of the APCCF-TBR, was compared with a TBR made using the polyvinyl chloride (PVC)-coated polyester fabric (PVCCF). The TBRs were used for the anaerobic fermentation process using baker's yeast; and, for aerobic fermentation process using filamentous fungi, primarily by using waste streams from ethanol industries as the substrates. The results from the fermentation experiments were similar with those that were obtained from the cultivations that were carried out in conventional bioreactors. The techno-economic analysis conducted using a 5000 m^3 APCCF-TBR for a typical fermentation facility would lead to a reduction of the annual production cost of the plant by $128,000,000 when compared to similar processes in SSBR. The comparative analyses (including mechanical and morphological studies, density measurements, thermal stability, ageing, and techno-economic analyses) revealed that the APCCF is a better candidate for the material of construction of the TBR. As the APCCF is a 100% recyclable single-polymer composite, which was prepared from Nylon 66 textile production-line waste, it could be considered as an environmentally sustainable product.

Keywords: single-polymer composite; textile bioreactor; all-polyamide coated-fabric; polyvinyl chloride (PVC) coated-textile; waste management; Nylon 66; yeast fermentation; edible filamentous fungi cultivation; techno-economic analysis

1. Introduction

'Energy'—its production and its use in contemporary society—is a formidable topic [1]. Renewable energies are being increasingly adopted across Europe, partly due to the European Union's (EU's) energy policy based on its 20-2020 commitments, i.e., 20% renewables by 2020 [2]. As biofuels must compete with fossil fuels, any attempt to reduce their investment and operational costs will contribute to stimulate their consumption [3]. During the last few years, several research projects have been conducted to minimise biofuel production costs [4], regarding the process technologies, as well as the equipment or infrastructure facilities, such as the bioreactors or distillation columns. A *bioreactor* is a vessel that provides an environment suitable for *fermentation* reactions where the controlled growth of microorganisms result in the production of biofuels [5]. Bioreactors are made out of stainless steel or concrete, which are expensive and time-consuming to install [5]. To be used as a bioreactor, the construction material has to meet several prerequisites, such as the ability to provide a suitable environment for the microbial proliferation, withstand high pressure [6], be inert to the underlying biological and chemical process conditions [3], corrosion proof, and water-proof and/or gas-proof, depending on the fermentation process. Recently, research studies have come-up with alternative material for making microbial bioreactors [3]. One such example is using polyvinyl chloride (PVC)-coated polyester fabric (hereafter referred as PVCCF). Polyester being one of the most conventional but less advanced fabric in the textile industry, could be replaced with a better performing textile, such as polyamide (PA) that possess a longer lifetime, has a higher mechanical and dimensional stability, and is light weighted [7]. However, for economic reasons polyester fabric has to be used as the base material in many cases. Nevertheless, the coating of the PVC onto the polyester fabric involves chemical formulations that might be harmful to the microorganisms. Additionally, the recycling of the materials used will also pose severe challenges, as it consists of the mixture of PVC, polyester fabric, a plasticizer for the PVC, chemical linkers, and some other processing-aid additives [8].

A possible solution to effectively address these issues is to use a coated-fabric composite made of a single material—single-polymer composite—called all-polyamide composite coated-fabric (APCCF), which is mechanically stronger and thermally stable and weighs less than PVCCF [9]. Additionally, APCCF is fully recyclable as it contains only a single material,l (PA) that is prepared by adhesion of the PA fabric and the PA solution made out of waste, making them a cost-effective and eco-friendly material [9]. In the perspective of environmental sustainability, the recycling of fabric and textiles decreases the use of natural resources, such as water or petroleum, that are being used for generating new fabric or textiles [10]. It also lowers the extent of chemical usage and the associated pollution that is encountered during the textile manufacturing process [11]. Currently, the most common method of recycling textiles is to use them as composite filler [12]. This method is however not effective as they do not maintain the quality or properties of the composites [13]. Hence, the development of a fabric-based bioreactor using recycled textile opens up the possibility of resource recovery and energy balance for an economically sustainable biofuel process.

This study hence introduces a novel and first-of-its-kind 'single-polymer composite'-based bioreactor, which is made from recycled textile or fabric waste. The potential application of APCCF bioreactor in a conventional ethanol industry was achieved by using it as a bioreactor for biofuel production using yeast and fungi to convert sugar and organic waste streams (thin stillage or vinasse) into valuable products (ethanol and protein-rich fungal biomass). A series of material performance analysis together with an economic analysis were also carried out to compare the performance and cost-effectiveness of APCCF-based bioreactor with the conventional bioreactors.

2. Materials and Methods

2.1. Material

Formic acid that was used in this study was supplied by Sigma-Aldrich (Saint Louis, MO, USA, ACS reagent grade, >98%). Acetic acid, ethanol, DL-lactic acid, glycerol, butyric acid, and acetone were purchased from Sigma-Aldrich and were used without further modifications. The PA66 plain woven fabric was provided by a local supplier. The PA66 fibre production waste from the weaving process at a local Swedish textile company (FOV Fabrics AB, Borås, Sweden) was used as a polymer source. Sugar-to-ethanol industry waste stream, vinasse, was provided by Sepahan Bio-product Company (Isfahan, Iran). Thin stillage, a residual product from the wheat-based first-generation ethanol facility, was provided by Lantmännen Agroetanol (Norrköping, Sweden). Both of the substrates were used directly without any further laboratory treatment and were stored at 4 °C cold room prior to its use. Detailed chemical characteristics of vinasse and thin stillage are described in previous studies [14].

2.2. Composite Material and Reactor Design

All-polyamide composites were prepared in the form of a flat laminate on the substrate fabric following an isothermal immersion-precipitation non-solvent induced phase separation (NIPS) method, according to our previous report [9]. The glass plate (carrying the fabric and a layer of the PA solution) was immersed in a distilled water bath at room temperature to induce polymer precipitation (phase separation) at the end of the casting process. The coagulation process (in the water bath to obtain the composites) was prolonged for 1 h, following which the composites were washed with distilled water (consecutively for at least 3–4 times) and were subsequently held under the filter-paper press to remove the moisture. The composites (hereafter referred to as APC sheet) were further dried at 55 °C in a vacuum oven (≈0.1 bar) for 2 h. For the lab scale APCCF bioreactor design, the APC sheets were attached at their sides and were glued using a commercial adhesive—Universal Power Epoxy (Loctite, Düsseldorf, Germany) to attain the shape of the bioreactor. To assure the adhesion, the adhesive-containing edges were placed under a hot press (60 °C and 220 kN) for 15 min. The detailed design of the fabric reactor is depicted in Figure 1. As the APCCF is made of PA, which is known as a thermally-resistant polymer, sterilization using heat (autoclave condition) will not have any detrimental effect on the properties of the composite. The thermal stability properties of the APCCF are tabulated in Figure 2. The reactor did not have any frame; hence, made as a stand-alone bioreactor. The cap (inlet/outlet) was a polyethylene bottle cap glued to the bioreactor using epoxy adhesive.

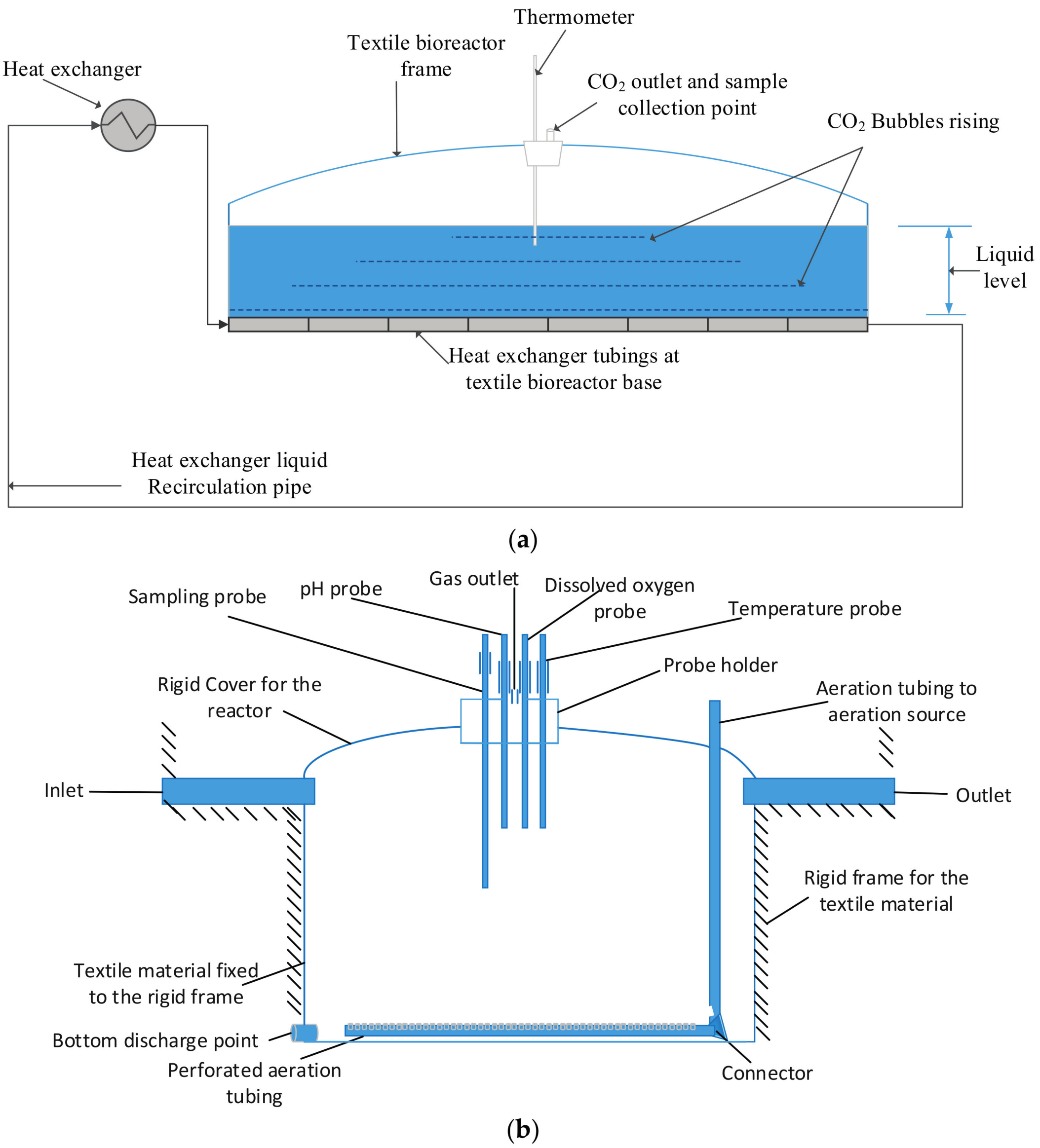

Figure 1. (**a**) Schematic of the laboratory scale prototype of the all-polyamide composite-coated-fabric (APCCF) bioreactor; (**b**) General schematic representation of APCCF bioreactor.

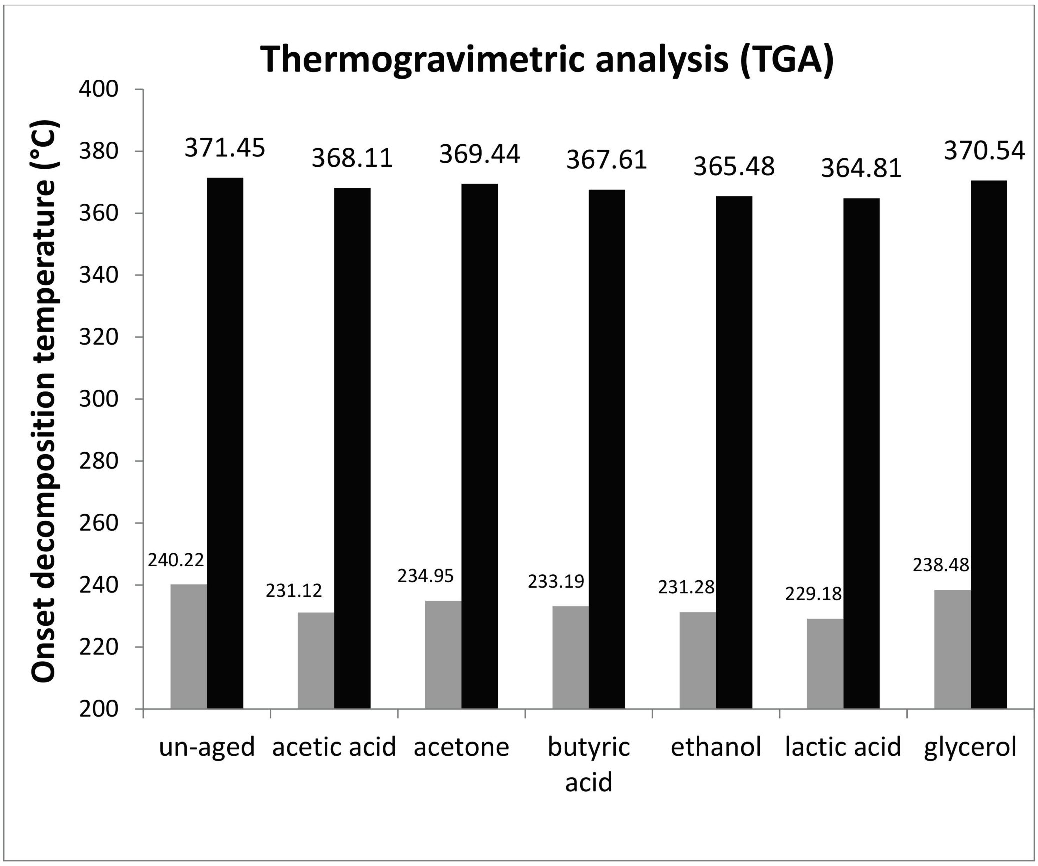

Figure 2. Comparative onset decomposition temperatures for polyvinyl chloride (PVC) coated-fabric (PVCCF) and APCCF samples in different conditions (un-aged: before the ageing test, the rest are corresponding to ageing the samples in various mediums). The dark-black corresponds to 'before ageing' and the grey columns correspond to the 'aged samples'.

Characterization of the Reactor Material

The water impermeability of the APCCFs was analysed using a dead-end diffusion cell. APC sheet with the diameter of 35 mm was placed in the cell, filled with 25 mL ultrapure water, with subsequent pressure (in the range 0.5, 1, 1.5, 2, and 2.5 bar) being applied to the cell using nitrogen gas. The APCCF sheet was shown to be highly water-proof, with no permeation even at a pressure of 2.5 bar. The tensile strength properties of the fabric fermenter material were evaluated in accordance with the ISO527 standard method [8]. The dumbbell-shaped test bodies (75 mm long, 4 mm width) were tested on an MTS 20/M tensile strength tester (MTS Systems Corporation, Eden Prairie, MN, USA), fitted with a 5 kN load cell and a special grip for films, using a crosshead speed of 5 mm/min. The gauge length, preload force, and first approach speed were 0.5 N, 2 mm/min and 33 mm, respectively. The thickness of the composites was measured by Elastocon thickness meter (Elastocon AB, Brämhult, Sweden). A minimum of five test bodies was tested for each material. The specimens were all cut in the warp direction of the fabric. To conduct the tensile strength comparison between the APCCF and PVCCF, the PVCCF was prepared according to the method previously reported [8]. The densities of the composites were obtained by dividing the weight of the composites by their volume. Measurements of the composites' weights were performed by using a balance to determine the most possible accurate weight, and the volume was measured by a graduated cylinder containing distilled water. Five specimens were tested for each composite.

The ageing test was performed in the following way: a piece of sample from either PVCCF and APCCF (70 mm × 20 mm) were cut with normal scissor and were placed in six different media, including acetic acid, ethanol, DL-lactic acid, glycerol, butyric acid, and acetone, all used in 100% purity. The beakers containing the samples and the media were kept at the room temperature for 14 days. Then, the samples were taken out, washed three times with distilled water subsequently three times with acetone. Then, the samples were dried in a ventilated oven at 50 °C for 24 h. The samples were analysed using the tensile strength testing machine and thermogravimetric analysis (TGA) Q500 machine (TA Instruments, MA, USA). About 10 mg of the material was heated from room temperature to 600 °C at a heating rate of 10 °C/min in a nitrogen purge stream.

2.3. Yeast Fermentation

Dry ethanol red yeast (Saccharomyces cerevisiae) from Fermentis (Strasbourg, France) was used to carry out the yeast fermentation experiments. A starting concentration of 10 g/L of the dry yeast was used for the process. Fermentation was performed in a 2 L laboratory scale prototype of the bioreactor with a working volume of 1 L at 30 °C. The dimensions of the bioreactor were 25 cm length, 20 cm breadth, and 4 cm width. A schematic of the lab scale prototype is shown in Figure 1a. Sucrose (280 g/L) was used as energy and carbon source, while 7.5 g/L $(NH_4)_2SO_4$, 3.5 g/L KH_2PO_4, 0.75 g/L $MgSO_4{\cdot}7H_2O$, and 1.0 g/L yeast extract were also added to supply additionally needed nutrients. Sucrose concentration dropped to 259.3 ± 1.5 g/L after the feed was autoclaved. Temperature control was carried out using a GD 120 grant thermostatic circulator (GD Grant Instrument Ltd., Cambridge, UK). The thermostatic circulator was connected to a 4 m PVC tubing, which was wound eight times and was placed at the bottom of the bioreactor to maintain the desired temperature.

2.4. Fungi Cultivation

A filamentous fungus Neurospora intermedia CBS 131.92 (Centraalbureau voor Schimmelcultures, Utrecht, The Netherlands) was maintained on potato dextrose agar (PDA) slants containing (in g/L): potato extract 4, D-glucose 20, agar 15, and the plates were renewed every six months. For the regular experimental purpose, the fungus was transferred to fresh PDA plates. The fungal plates were then incubated aerobically for three to five days at 30 °C. For preparing spore suspension, fungal plates were flooded with 20 mL sterile distilled water and the spores were released by gently agitating the mycelium with a disposable cell spreader. An inoculum of 50 mL spore suspension per L medium with a spore concentration of $6.3 \pm 0.8 \times 10^5$ spores/mL was used for the cultivations. The fungal cultivations were carried out aerobically in thin stillage, and vinasse using 3 L capacity APCCF bioreactor, with a total working volume of 2 L. Aeration at the rate of 1.0 vvm ($volume_{air}/volume_{media}/min$) was maintained throughout the cultivation, using a perforated sparger with a pore size of 100 µm. Filtration of the inlet air was achieved by using a membrane filter (0.1 µm pore size, Whatman, Florham Park, NJ, USA). Samples were collected every 24 h and were stored at 4 °C until analyses (unless otherwise specified). Temperature control was carried out using a GD 120 grant thermostatic circulator (GD Grant Instrument Ltd., Cambridge, UK). The pH was adjusted with either 2 M HCl or 2 M NaOH.

All of the experiments and analyses were carried out in duplicate and the results were reported with error bars and intervals representing two standard deviations.

2.5. Fermentation Analyses

High-Performance Liquid Chromatography-HPLC system (Waters 2695, Waters Corporation, USA) was used to analyze all liquid fractions from the fermentation experiment. A hydrogen-based ion-exchange column (Aminex HPX-87H, Bio-Rad Hercules, CA, USA) at 60 °C with a Micro-Guard cation-H guard column (Bio-Rad) and 0.6 mL/min 5 mM H_2SO_4 (eluent), was used with a refractive index detector (Waters2414, Waters Corporation, Milford, MA, USA) and a UV detector (Waters 2487). The samples that were used for the HPLC analysis were centrifuged for 10 min at 10,000 × g and the liquid portion stored for analysis. The samples were stored at −20 °C prior to HPLC analysis. All of the experiments and analyses were carried out in duplicate and the results are reported with error bars and intervals representing two standard deviations. The yield from the fermentation experiment was calculated using concentration values after autoclaving, as reported by the HPLC.

2.6. Economic Analysis

The investment cost that was needed for procurement of stainless steel, the predominating material of construction for the conventional bioreactors used by the industries [3], was estimated using Equation (1):

$$C = F_m \exp[11.662 - 0.6104(\ln V) + 0.04536(\ln V)^2] \quad (1)$$

where C is cost ($) F_m is 2.4 for 304 stainless steel and V is volume (gallons) [15]. The procuring cost of the stainless steel reactors was updated to 2017 using the projected Chemical Engineering Plant Cost Index (CEPCI) for 2017, which was 574.1, based on the current low oil price [16]:

$$C_{updated} = C\,(I_{updated}/I) \quad (2)$$

The purchasing cost of the fabric material for reactor construction was obtained from the estimates at a local textile company in Borås, Sweden. The investment cost in the bioreactor is a key part of the capital expenditure on the fermentation or waste-to-product transformation process. It influences the cost of handling waste or production of the desired products, as shown in Equation (3) [17], where FC is the cost of feedstock ($/tonnes), Y is product yield (m^3/tonne), ACE is the annual capital expenditure ($/$m^3$), OC is the operation cost ($/$m^3$), Ye is the electricity yield (kWh/m^3), and EC is electricity credit ($/kWh):

$$\text{Annual production cost (APC)} = FC/Y + (ACE + OC) - Ye.EC \quad (3)$$

3. Results and Discussion

To overcome the challenges that are associated with the conventional microbial bioreactors, a robust polymer composite (APCCF) was used to prepare the textile bioreactor in this study. A PA-coated PA fabric single-polymer composite (based out of PA66) was prepared in the study to address the issues surrounding the current coated-fabrics (material of construction of textile-bioreactors (TBRs)), such as the recyclability, the adhesion between the coating, and the fabrics. This was achieved by applying the PA66 solution to the PA fabric using a universal film applicator with subsequent coagulation in a water bath, to induce phase separation (phase inversion). Hence, a composite composed of a thin continuous PA layer (the coating) and a PA textile fabric encompassing the most common type of aliphatic polyamide (PA66) was obtained, which forms the base material for the APCCF bioreactor.

3.1. Material Development

Mechanical stability of materials that are used for constructing bioreactors is generally of high importance [5]. Both stainless steel and concrete, which are conventionally being used for bioreactor construction, have got higher levesl of tensile strength than any available commercial polymer. The fabric-based bioreactor possesses several merits, such as being cost-effective, less time consuming to install, easiness with transportation, and foldability. However, the bioreactors made from PVCCF will have several challenges, such as being susceptible to shear stresses, and in some cases, the delamination (detaching of the coating from the fabric). The results from this study suggest that in the all-polyamide composite-coated-fabric (APCCF), the mechanical properties have been improved (Table 1). Hence, it was clear that the APPCF has superior mechanical properties (increase by around 20%) than the PVCCF. This could be attributed to the nature of the polymers. PA generally contains amide groups that are prominent acceptor/donator in the hydrogen-bonding [18,19], which establishes strong intermolecular interactions. However, PVC by nature does not have strong intermolecular interaction; therefore, it is more susceptible to fast-breaking. Hence, the APCCF could be more robust, resulting in an extended lifetime for the APCCF bioreactor material.

Table 1. Comparison between the tensile strength properties of PVC-coated polyester fabric (PVCCF) and all-polyamide composite-coated-fabric (APCCF). Un-aged samples are the ones before ageing.

Medium	PVCCF	Δ (%)	APCCF	Δ (%)
un-aged	57.2 ± 2.19	n.d.	68.6 ± 1.77 *	n.d.
acetic acid	49.8 ± 1.71	12.9	63.2 ± 1.21	7.9
acetone	52.5 ± 2.3	8.2	67.3 ± 1.9	1.9
butyric acid	53.1 ± 1.8	7.2	65.7 ± 1.61	4.2
ethanol	55.3 ± 1.6	3.3	67.4 ± 1.2	1.7
lactic acid	51.2 ± 1.4	10.5	63.1 ± 2.1	8.0
glycerol	55.1 ± 1.7	3.7	68.1 ± 1.4	0.7

* The numbers after '±' represent the standard deviations.

In the ageing test, the APCCF as well as the PVCCF, were kept in six different organic solvents, which are the most commonly produced metabolites in the microbial processes [20]. According to the results (Table 1), in all of the test solvents, both APCCF and PVCCF were affected with a decline in its mechanical properties; however, in all of the cases, the decrease in tensile strength value for the APCCF were lower than the one for the PVCCF. For acetic acid, which is the second strongest unmodified organic acid (after formic acid), the PA chain was found interacting with acetic acid molecules.

According to Chen et. al. [21], there is an interaction between acids and the PA polymer at the surface. The aforementioned interaction can weaken the intramolecular interactions, as each of the amide groups can only have two hydrogen bonding interactions with other amide groups. While there is better hydrogen bonding, donor/acceptor exists in the vicinity of the surface PA chain, the amide groups prefer them and loosen the previous interaction with the inner PA chains. In this case, acetic acid is a better hydrogen bonding acceptor (due to having a partially negative charge on the oxygen in its carbonyl) and a better hydrogen bonding donator from the acidic hydrogen. Apart from this interaction, as PA can behave like a base, there could be another interaction in the form of acid/base interaction. Both of these two interactions decrease the internal chains (from the surface towards the bulk of the polymer), which leads to the decrease in crystallinity of the polymer, which in turn decreases the tensile strength value. This is the case with other acids (lactic/butyric acid) with the difference in the intensity of the effect.

Butyric acid has the same structure similar to acetic acid, with a longer hydrophobic chain, which in this case, decreases the hydrogen bonding ability. The lower hydrogen bonding ability is due to having a longer electron-donor alkyl group that decreases the density of partially positive charge on the carbon atom in the carbonyl group, which in turn decreases the difference in charge density between carbon and oxygen in the carbonyl group. Furthermore, the longer aliphatic chain decreases the mobility of the molecule and creates a bigger repellence between the butyric acid molecule and the PA chain, which leads to less interaction between them [22]. Less interaction between the PA and butyric acid means that more intramolecular interactions will remain. Hence, the crystallinity will be changed less. It can be confirmed with the tensile strength values in Table 1.

For the case of lactic acid, although it has a longer aliphatic chain than acetic acid, it has one more hydrogen bonding site —hydroxyl group— which will increase the interactions between lactic acid and PA. That might be the reason of a lower measured value for lactic acid than acetic acid in tensile strength testing. The values for ethanol and glycerol are reasonable with the above proposal; however, for acetone, which has less hydrogen bonding ability when compared to all of the other five solvents, the decrease in the tensile strength value should not be more than the one for glycerol, if the above proposal is correct. We assume that there might be other interactions involved between acetone and PA, which needs to be elaborated in a separate study. Although the action of the chemical substances towards the materials of construction of the bioreactor might be weak (as cultivation media mainly consists of water), we used the pure chemicals to accelerate the ageing process. Since the ageing study was a comparative-based study between APCCF and PVCCF, the effect of the chemicals' concentration would be the same for both composites. Hence, the results could be assumed as meaningful findings.

PVC is also affected by protic and polar solvents [23]. The reason for more decrease in tensile strength value for PVCCF when compared to APCCF in different mediums could be related to the reason that PVC contains a soft chlorine ion in its structure, which increases the tendency of establishing hydrogen binding between the surface PVC chains and the medium surrounding it. Also, PVC in nature is a more amorphous polymer when compared to PA [24,25], which makes it more susceptible towards surrounding chemicals/medium.

Figure 2 shows the TGA results for the un-aged samples and the samples that are aged in six different solvents. Similar to the above proposal for the tensile strength testing, in all of the cases, there is a decrease in the onset decomposition temperature (ODT) value after ageing, which could be related to the hydrogen bonding (discussed above). Although the differences are not significant, the decrease in ODT values for APCCF samples are less than the ones for APCCF, meaning that APCCF has superior thermal stability. Though the textile bioreactor will never experience those high temperatures (e.g., 300–400 °C), having a higher ODT value (both in un-aged and aged samples) will give a better long-term stability to the APCCF [26]. From the tensile strength testing and TGA results, both in the un-aged sample and in the aged samples in different mediums, we can conclude that APCCF is a better candidate for making textile bioreactor than PVCCF. As the APCCF has the ODT (371 °C) above the autoclave temperature (121 °C), one can assume that the APCCF as an 'autoclave-proof' material.

PA is a polymer containing monomers of amides joined by peptide bonds. They can either occur naturally (for instance, proteins such as wool and silk) or can be made artificially, for example, nylons, aramids, and sodium poly (aspartate). According to McCrum and Buckley [27], in general, polyamides presents a proper conciliation between toughness and strength with a low coefficient of friction and high thermal resistance (melting temperatures above 200 °C and thermal deflection—under low load superior to 160 °C). Using this polymer can hence impart superior properties to the fabric bioreactor rather than using other commercially available polymers. Polyamide 66, with its high abrasion properties together with the high strength, can be considered as the most suitable candidate polymer for the development of fabric bioreactor. Polyamide 66, hence imparts high strength (withstanding the high pressure of fermentation media inside the reactor), as well as enough chemical resistance towards the chemical or biological process occurring within the reactor.

Figure 3 demonstrates the cross-sectional morphology of the two coated-fabrics. One can observe that only a few of the fibre-filaments in the PVCCF are attached to the coating, while in the APCCF, almost all of the fibre-filaments in the first row of the side of the fabric facing to the coating are adhered to the coating as well as adhering to each other. Adhesion on coating industries plays a crucial role [28]. If the adhesion is not good enough, then the coating will be detached from the fabric after a certain time, called delamination [29]. In our case, the adhesion is much enough for the first-row fibre-filaments to be fused to each other. The fibre-filaments not only are adhered to the coating but are also fused to each other making the coating stronger.

Figure 4 shows the comparative density of the PVCCF and APCCF. PVCCF is composed of two main ingredients, PVC and polyester, which are heavy in comparison with other conventional polymers [30]. PVC and polyester are both heavier (in volume/mass unit) than PA—the sole ingredient of the APCCF, making APCCF a lighter material. The decrease in density (by around 16%) shows that the transportation cost of the bioreactor would be lower and also it would be easier. On the other hand, the total weight of the reactor in case of using APCCF as the material of construction of the bioreactor would be less than the cost of the PVCCF one.

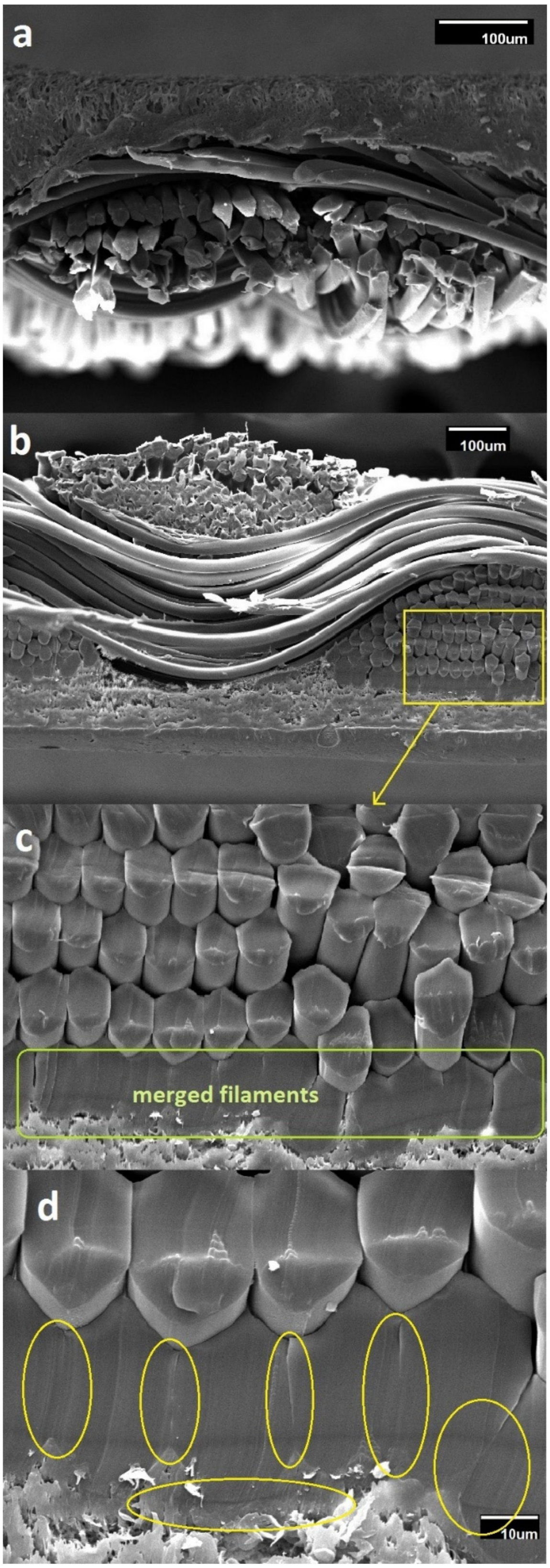

Figure 3. Cross-sectional SEM picture of PVCCF (**a**) and APCCF (**b**,**c**). The fused parts are shown with the yellow ovals (**d**). In PVCCF, the adhesion is not homogeneous and strong while in APCCF, the first row of the fibre-filaments of the PA fabric are merged together and adhered to the coating. It will decrease the chance of delamination in a long span of time.

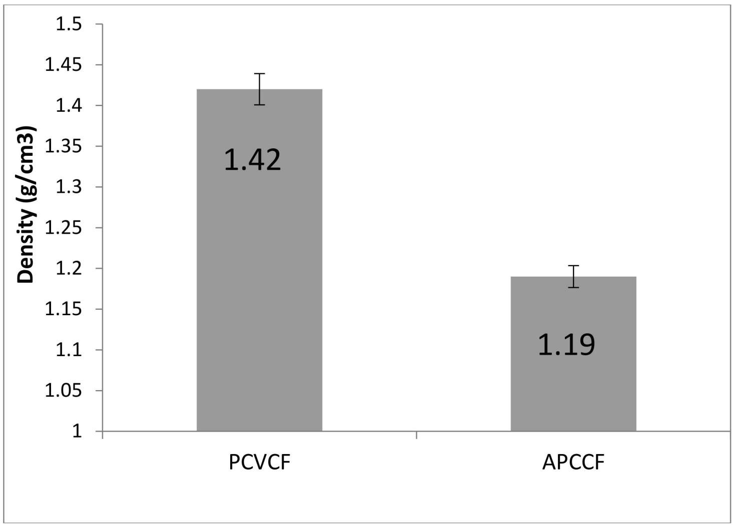

Figure 4. The comparative density of the PVCCF and APCCF. PVCCF is composed of two main ingredients: PVC and polyester which both are heavier in volume/mass unit than that of polyamide—the sole component of the APCCF, resulting in a lighter material.

PA chains contain amide groups (a weak organic base), so they are not susceptible to mild acidic conditions (up to pH > 3), that represents the pH conditions of most fermentation media (pH 5–7). In this regard, polyolefins (polyethylene and polypropylene) are also comparable with polyamides; however, they are not readily soluble, unlike polyamides, hence posing potential challenges during the production process. Another excellent property of PA that makes it the sole material for the single-polymer composite is its thermal stability. Due to the presence of nitrogen along with the hydrogen atoms on each polymer chain, they pose strong hydrogen bonding that hinders the disentanglements of the chains, which in-turn limits the thermal decomposition of the polymer. However, the argument that the fabric-based bioreactor will never experience high temperatures (more than 40–50 °C), which also eliminates the need to consider the onset thermal decomposition temperature for this material, could remain valid. Nevertheless, the long-term exposure of the industrial scale APCCF bioreactor to the atmospheric temperature (around 35 °C) could be considered since the polymers will thermally decompose both at high temperatures (for the relatively short time) and also at moderate/low temperatures for a longer exposure time. In this regard, the use of material such as PA66, with a higher thermal resistance will guarantee a longer shelf-life for the bioreactor. Additionally, in an environmental perspective, the use of single-polymer composite material (i.e., PA66) that is recycled from the textile industry presents the opportunity for making the fabric based reactor an environmentally sustainable product.

3.2. APCCF Bioreactor for Valorization of Waste-Stream from Conventional Ethanol Industries

Introduction of the APCCF bioreactor to the conventional ethanol industries that follows either starch or sugar-based processes was achieved by using edible filamentous fungi. The use of filamentous fungi for generating value-added products from ethanol industry waste streams, such as thin stillage (from the starch-based process) or vinasse has been previously studied in conventional bioreactors [14]. Comparable results were obtained from the present study using the fungus neurospora intermedia, proving the potential application of fabric bioreactor (APCCF bioreactor) for filamentous fungi cultivation. The results from the fermentation of thin stillage and vinasse in the fabric are depicted in Figure 5. Fermentation of thin stillage resulted in the formation of 3.5 ± 0.3 g/L of dry weight fungal biomass corresponding to a biomass yield 24.6% from the total fermentable sugar, which is comparable to 4 g/L of dry weight biomass obtained from bubble column bioreactor that used thin stillage for a continuous cultivation process [14]. An ethanol maximum of 4.9 ± 0.6 g/L was observed at the cultivation time of 36 h with a high rate of fermentable sugar assimilation within the first 24 h of fungal growth (93.3% reduction). Similarly, the fermentation of vinasse at a dilution rate of 10% resulted in the formation of 8.5 ± 0.7 g/L of dry weight fungal biomass. The higher fungal biomass production in vinasse could be attributed to the presence of essential mineral components that are present in it, which support prolific fungal growth. As opposed to the thin stillage cultivation, a much slower sugar assimilation rate was observed with vinasse, with only 22.2% reduction within the first 24 h. However, the complete utilization of the fermentable sugar was observed within the next 12 h, with no sugar being left after 36 h of the cultivation time (Figure 5). Cultivations at the pilot scale APCCF bioreactor resulted in the growth of fungal biomass that attributes for a total crude protein content of 51%.

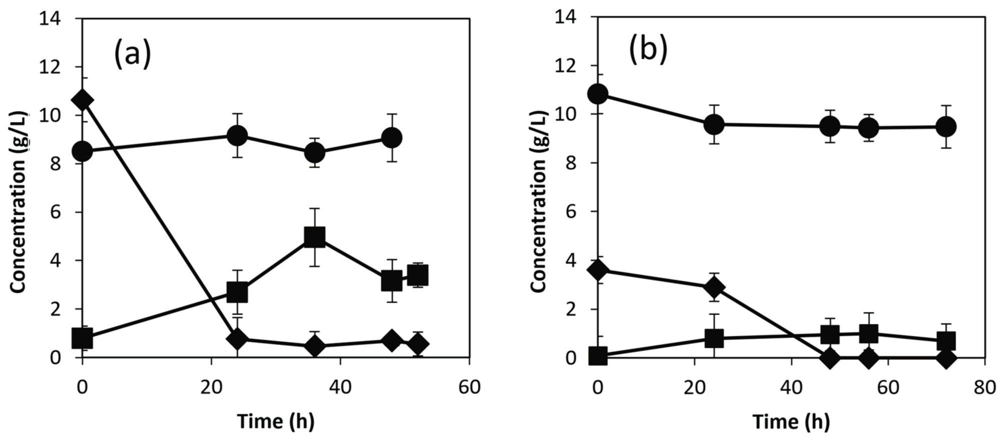

Figure 5. Fermentation of thin stillage (**a**) and vinase (**b**) in the textile bioreactor showing total fermentable sugar (◆), ethanol (■), and glycerol (●).

3.3. APCCF Bioreactor for Conventional Ethanol Production

Fermentation was carried out in the lab scale prototype of the APCCF bioreactor at 30 °C and pH of 6.0 ± 0.2 using the ethanol-producing yeast as explained in Section 2.3. The result of the fermentation is shown in Figure 6. Ethanol yield 96.3% of the theoretical maximum was attained using average ethanol concentration during the stationary phase. Ethanol specific productivity and substrate-specific consumption rate of 4.0 g/L/h and 0.7 g/g/h were attained in the bioreactor, which are comparable to the reported values from sugarcane-based ethanol production facilities [31,32].

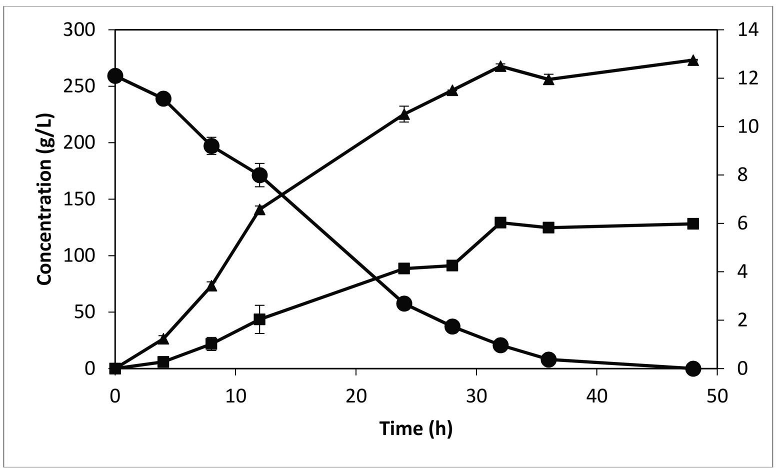

Figure 6. Fermentation performed in the lab scale prototype of textile bioreactor at 30 °C showing sucrose (●), ethanol (■) in the primary axis and glycerol (▲) in the secondary axis.

3.4. Economic Evaluation and Cost Comparisons

A cost-competitive bioreactor installation is one of the many opportunities that are currently evaluated to create an economically sustainable biofuel process. The procuring cost of conventional stainless steel bioreactor vessels at different volumes was estimated using Equations (1) and (2), as depicted in Table 2. Similarly, the procurement cost of varying textile bioreactor volumes is also shown in Table 2. It can be observed that the textile bioreactor capital investment cost is at least thrice less expensive than the cheapest of the stainless steel reactor that meets the requirements of a bioreactor, which is 304-stainless steel.

Table 2. Comparative procurement cost for APCCF bioreactor and 304-SSBR vessels.

Reactor Size (m^3)	Purchase Cost of Developed TBR ($)	Purchase Cost of 304 SSBR ($)
100	25,000	108,000
200	35,000	137,000
300	45,000	160,000
400	58,000	181,000
500	66,000	200,000

The estimated operation and investment cost of a stainless steel reactor is 1.7 times of its procurement cost after it has been installed [15], while that for a fabric bioreactor is 1.5 times of its procurement cost for a 15 year period [33]. This contributes to the annual production cost, as shown in Equation (3). Assuming that the production facility requires a 500-m^3 bioreactor for producing the desired product, and the capital expenditure is depreciated using straight-line depreciation for 15 years. The developed bioreactor would contribute $7700/$m^3$/year to the annual production cost, while the stainless steel bioreactor would contribute $33,333/$m^3$/year to the annual production cost. If 5000 m^3 of feedstock is processed in a year, using the currently developed bioreactor would potentially lead to a reduction of the annual production cost by $128,000,000.

4. Conclusions

A textile-bioreactor, prepared using the industrial waste polymer (all-polyamide composite coated-fabric (APCCF)), was introduced in this study. The tensile strength testing, density measurements, ageing test, and thermal stability analyses showed that the APCCF poses superior characteristics than the PVCCF—the material that is currently being used to prepare the conventional textile-bioreactors. Hence, APCCF could be considered as a better candidate for the material of construction of the textile-bioreactors. Introduction of the APCCF bioreactor to the ethanol industry was achieved using yeast for ethanol production and filamentous fungi for generating value-added products, such as fungal biomass protein, using the waste streams from the ethanol industry. The fungal fermentation and the economic analysis of the textile bioreactor showed comparative results with the conventional bioreactors. In an environmental perspective, the use of single-polymer composite material (i.e., polyamide 66) that is recycled from the textile industry, presents the opportunity for making the fabric-based bioreactor an environmentally sustainable product.

Acknowledgments: The authors would like to acknowledge FOV Fabrics AB (Borås, Sweden) for providing the polyamide fabric, the PVC-coated polyester fabric and the polyamide 66 scraps. This project was financially supported by University of Borås, Borås, Sweden and FOV Fabrics AB.

Author Contributions: M.J. developed and designed the bioreactor; M.J., R.B.N., and O.A.O. conceived, designed, and performed the experiments; M.J., O.A.O., and R.B.N. contributed to analyzing the data and writing the paper; M.J.T. supervised the study and revised the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wilson, D.G. Energy supplies and future engines for land, sea, and air. *J. Air Waste Manag. Assoc.* **2012**, *62*, 607–624. [CrossRef] [PubMed]
2. Arteconi, A.; Hewitt, N.J.; Polonara, F. Domestic demand-side management (dsm): Role of heat pumps and thermal energy storage (tes) systems. *Appl. Therm. Eng.* **2013**, *51*, 155–165. [CrossRef]
3. Osadolor, O.A.; Lennartsson, P.R.; Taherzadeh, M.J. Introducing textiles as material of construction of ethanol bioreactors. *Energies* **2014**, *7*, 7555–7567. [CrossRef]
4. Palacios-Bereche, R.; Ensinas, A.; Modesto, M.; Nebra, S.A. New alternatives for the fermentation process in the ethanol production from sugarcane: Extractive and low temperature fermentation. *Energy* **2014**, *70*, 595–604. [CrossRef]
5. Blakebrough, N. Fundamentals of fermenter design. *Pure Appl. Chem.* **1973**, *36*, 305–316. [CrossRef]
6. Osadolor, O.A.; Lundin, M.; Lennartsson, P.R.; Taherzadeh, M.J. Membrane stress analysis of collapsible tanks and bioreactors. *Biochem. Eng. J.* **2016**, *114*, 62–69. [CrossRef]
7. Chernukhina, A.I.; Gabrielyan, G.A. Thermostabilization of aliphatic polyamides and fibres on their base (review). *Khimicheskie Volokna* **1993**, 30–34.
8. Jabbari, M.; Åkesson, D.; Skrifvars, M.; Taherzadeh, M.J. Novel lightweight and highly thermally insulative silica aerogel-doped poly(vinyl chloride)-coated-fabric composite. *J. Reinf. Plast. Compos.* **2015**, *34*. [CrossRef]
9. Jabbari, M.; Skrifvars, M.; Åkesson, D.; Taherzadeh, M.J. Introducing all-polyamide composite coated-fabrics: A method to produce fully recyclable single-polymer composite coated-fabrics. *J. Appl. Polym. Sci.* **2016**, *133*, 42829. [CrossRef]
10. Angelov, R.R.; Georgieva, B.C.; Karashanova, D.B. Films of recycled polyethylene terephthalate, obtained by electrospraying, for paper and textile impregnation. *Bulg. Chem. Commun.* **2016**, *48*, 156–160.
11. Riley, K.; Williams, J.; Waldron, D. End of life opportunities for textiles in the UK healthcare sector. *J. Fiber Bioeng. Inform.* **2009**, 709–717.
12. Sommers, J.; Kho, H.S.; Al-Ghamedi, R.; Low, I.M.; Davies, I.J.; Latella, B.A. Mechanical and physical properties of recycled cellulose fibre-reinforced epoxy eco-composites. *Adv. Mater. Res.* **2008**, *41–42*, 317–322. [CrossRef]
13. Low, I.M.; Somers, J.; Kho, H.S.; Davies, I.J.; Latella, B.A. Fabrication and properties of recycled cellulose fibre-reinforced epoxy composites. *Compos. Interfaces* **2009**, *16*, 659–669. [CrossRef]
14. Ferreira, J.A.; Lennartsson, P.R.; Taherzadeh, M.J. Production of ethanol and biomass from thin stillage by neurospora intermedia: A pilot study for process diversification. *Eng. Life Sci.* **2015**, *15*, 751–759. [CrossRef]
15. Couper, J.R.; Penney, W.R.; Fair, J.R.; Walas, S.M. Costs of individual equipment. In *Chemical Process Equipment*; Elsevier Inc.: Amsterdam, The Netherlands, 2005; pp. 663–669.
16. Mignard, D. Correlating the chemical engineering plant cost index with macro-economic indicators. *Chem. Eng. Res. Des.* **2014**, *92*, 285–294. [CrossRef]
17. Bergeron, P. Bioethanol market forces. In *Handbook on Bioethanol: Production and Utilization*; Wyman, C., Ed.; CRC Press: Boca Raton, FL, USA, 1996; pp. 61–88.
18. Vinken, E.; Terry, A.E.; Spoelstra, A.B.; Koning, C.E.; Rastogi, S. Influence of superheated water on the hydrogen bonding and crystallography of piperazine-based (co)polyamides. *Langmuir* **2009**, *25*, 5294–5303. [CrossRef] [PubMed]
19. Behler, K.; Havel, M.; Mattia, D.; Gogotsi, Y. Self-assembled multi-walled carbon nanotube coatings. In Proceedings of the Materials Research Society (MRS) Fall Meeting, Boston, MA, USA, 1–5 December 2008; pp. 133–138.
20. Sathitsuksanoh, N.; George, A.; Zhang, Y.H.P. New lignocellulose pretreatments using cellulose solvents: A review. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 169–180. [CrossRef]
21. Chen, F.; Chang, W.V. Applicability study of a new acid-base interaction-model in polypeptides and polyamides. *Langmuir* **1991**, *7*, 2401–2404. [CrossRef]
22. Carey, F.A.; Sundberg, R.J. *Advanced Organic Chemistry*; Springer Science & Business Media: Berlin, Germany, 2000.
23. Herrero, M.; Tiemblo, P.; Reyes-Labarta, J.; Mijangos, C.; Reinecke, H. PVC modification with new functional groups. Influence of hydrogen bonds on reactivity, stiffness and specific volume. *Polymer* **2002**, *43*, 2631–2636. [CrossRef]

24. Bao, Y.; Weng, Z.; Huang, Z.; Pan, Z. The crystallinity of pvc and its effect on physical properties. *Int. Polym. Process.* **1996**, *11*, 369–372. [CrossRef]
25. Gilbert, M. Importance of crystallinity in pvc. *Prog. Rubber Plast. Technol.* **1993**, *9*, 143–158.
26. Rathi, S.; Dahiya, J.B. Effect on thermal behaviour of polyamide 66/clay nanocomposites with inorganic flame retardant additives. *Indian J. Chem. A* **2012**, *51*, 1677–1685.
27. Buckley, R.W. *Polymer Enhancement of Technical Textiles*; iSmithers Rapra Publishing: Akron, OH, USA, 2003.
28. Sargent, J.G.; Lee, J.S.; Reynaud, E.; Gilbert, M.D.; Sloan, J.M. Study of selectively permeable coatings to textiles. In Proceedings of the 2010 Materials Research Society (MRS) Fall Meeting, Boston, MA, USA, 29 November–2 December 2011; pp. 497–502.
29. Rohwerder, M.; Stratmann, M. From molecular aspects of delamination to new polymeric coating. *Macromol. Symp.* **2002**, *187*, 35–42. [CrossRef]
30. Lodi, P.C.; De Souza Bueno, B.; Vilar, O.M. The effects of weathering exposure on the physical, mechanical, and thermal properties of high-density polyethylene and poly (vinyl chloride). *Mater. Res.* **2013**, *16*, 1331–1335. [CrossRef]
31. Basso, L.C.; Basso, T.O.; Rocha, S.N. Ethanol production in brazil: The industrial process and its impact on yeast fermentation. *Biofuel Prod. Recent Dev. Prospects* **2011**, 86–100.
32. Rajoka, M.I.; Ferhan, M.; Khalid, A.M. Kinetics and thermodynamics of ethanol production by a thermotolerant mutant of saccharomyces cerevisiae in a microprocessor-controlled bioreactor. *Lett. Appl. Microbiol.* **2005**, *40*, 316–321. [CrossRef] [PubMed]
33. Rajendran, K.; Aslanzadeh, S.; Johansson, F.; Taherzadeh, M.J. Experimental and economical evaluation of a novel biogas digester. *Energy Convers. Manag.* **2013**, *74*, 183–191. [CrossRef]