

## **All-polyamide composite coated-fabric as a replacement for material of construction of conventional textile bioreactors**

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

Swedish Centre for Resource Recovery, University of Borås, SE 50190 Borås, Sweden

\*Corresponding author: Mostafa Jabbari

Tel: +46 33 4354636

Fax: +46 33 4354003

E-mail: mostafa.jabbari@hb.se

## Abstract

All-polyamide composite coated fabric (APCCF) materials were developed and used as the material of construction of textile bioreactors as a replacement of traditional costly steel-/concrete-based bioreactors. Then, APCCF-bioreactor was used to cultivate filamentous fungus *Neurospora intermedia* to produce ethanol and fungal biomass. The results showed similar performance of the fungus cultivated in stain-less steel bioreactors. Techno-economical analysis for a 5000-m<sup>3</sup> APCCF bioreactor for fermentation facility would lead to a reduction of the annual production cost of the facility by \$128,000,000 compared to similar stainless-steel processes. The comparative analyses (including mechanical and morphological analyses, density measurements and techno-economical analysis) revealed that the APCCF is a better candidate for material of construction of the textile bioreactor. The APCCF is a 100% recyclable single polymer composite which was prepared from textile production line waste.

## Keywords:

single-polymer composite; bioreactor; textile reactor; fungal cultivation; economic analysis; polyamide; polyvinyl chloride

## 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 EU's energy policy based on its 20-2020 commitments, i.e. 20% renewables by 2020 [2]. As the 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 reduce the biofuel production costs [4], in terms of the process technologies as well as the equipment or infrastructure facilities such as the bioreactors or distillation columns. Bioreactor is a vessel that provides an environment suitable for the fermentation reaction where controlled growth of a microorganism happens to produce biofuel [5]. Generally 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 being corrosion proof, ability to provide suitable environment for the microbial proliferation, being inert to the underlying biological and chemical process conditions [3], withstand high pressure [6]. Recently, research studies have come-up with alternative material for making microbial fermenter [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 better performing textile, such as polyamide (PA) that generally possess longer lifetime, have 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 for the microorganisms. Additionally, the recycling of the materials used will also poses severe challenges, as it involves the mixture of PVC, polyester fabric, plasticizer for the PVC, chemical linkers, and some other processing-aid additives [8].

A possible solution to efficiently address these issues is to use a coated-fabric composite made out of one single material –single-polymer composite– called all-polyamide composite-coated fabric (APCCF), which is mechanically stronger and thermally stable and light-weighted than the PVCCF [9].

Additionally, the APCCF is fully recyclable as it contains only one single polyamide that is prepared by adhesion of the polyamide and the recycled fabric or waste, making them a cost-effective material [9]. In the perspective of an 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 decreases the extend of chemical usage and the associated pollution 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 introduces a novel and first of its kind APC-based fabric bioreactor 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 filamentous fungi cultivation, to convert the waste streams (thin stillage or vinasse) into valuable products (ethanol and protein rich fungal biomass). An economic analysis was 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

The formic acid used in this work was supplied by Sigma-Aldrich (ACS reagent grade, >98%). The PA66 plain woven fabric was provided by a local supplier. The polyamide fiber 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 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 the vinasse and thin stillage are described in previous studies [14, 15].

### 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 [9]. The glass plate (carrying the fabric and a layer of the polyamide 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 subsequently held under 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 ( $\approx 0.1$  bar) for 2 hours. For the lab-scale APCCF bioreactor design, the APC sheets were attached at their sides and glued using an epoxy adhesive 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 minutes. The detailed design of the fabric reactor is depicted in Figure 1.

### 2.2.1. Characterization of the reactor material

The water impermeability of the APC sheets were analyzed 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) 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 properties of the fabric fermenter material were evaluated in accordance with the standard method ISO527 [8]. The dumbbell shaped test bodies, 75 mm long (with the width of 4 mm), were tested on a MTS 20/M tensile tester (MTS Systems Corporation, Eden Prairie, MN), 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, 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 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 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 6 different media

including: acetic acid, ethanol, DL-lactic acid, glycerol, butyric acid, and acetone. The beakers containing the samples and the media were kept in 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 in 50 °C for 24 hours. The samples were analysed using tensile 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. Fungal strains

A filamentous fungus *Neurospora intermedia* CBS 131.92 (*Centraalbureau voor Schimmelcultures*, Netherlands) was maintained on potato dextrose agar (PDA) slants containing (in g/L): potato extract 4, D-glucose 20, agar 15 and the slants were renewed every six months. For the regular experimental purpose, the fungus was transferred to fresh PDA plates containing (in g/L): potato extract 4, D-glucose 20 and agar 15. The fungal plates were then incubated aerobically for 3 to 5 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.

### 2.4. Fungi cultivation in APCCF bioreactor

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 ( $\text{volume}_{\text{air}} / \text{volume}_{\text{media}} / \text{min}$ ) 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  $\mu\text{m}$  pore size, Whatman, Florham Park, NJ, USA). Samples were collected every 24 h and stored at 4°C until analyses (unless otherwise specified). The pH was adjusted with either 2 M HCl or 2 M NaOH. All experiments and analyses were carried out in duplicate and results reported with error bars and intervals representing two standard deviations.

#### 2.4.1. Pilot testing trials

Pilot testing of the fungal cultivation on sugar industry waste vinasse was carried out in a 20 L APCCF bioreactor. Fermentation was initiated by addition of *N. intermedia* inoculum (5-6 g mycelial wet weight per cultivation) to the spent wash media (10% dilution), supplemented with sucrose (20 g/L) and potato extract (5 g/L). The cultivations were carried out for 32 h, with biomass collected at the end of the cultivation.

#### 2.5. Analyses

Initial fungal spore concentration (in laboratory testing) was measured using a Bürker counting chamber (with a depth of 0.1 mm) under a light microscope (Carl Zeiss Axiostar plus, Germany). Fungal biomass concentration (dry weight) was determined at the end of the cultivation by washing the pellet or mycelial biomass with deionized water followed by drying at 105°C for 24 h before weighing. A digital Vernier caliper (Limit, Sweden) with the resolution of 0.01 mm was used to measure the pellet diameter. High Performance Liquid Chromatography-HPLC system (Waters 2695, Waters Corporation, USA) was used to analyze all liquid fractions from the fungal cultivations. A hydrogen-based ion-exchange column (Aminex HPX-87H, Bio-Rad Hercules, CA, U.S.A.) at 60°C with a Micro-Guard cation-H guard column (Bio-Rad) and 0.6 mL/min 5 mM H<sub>2</sub>SO<sub>4</sub> (eluent), was used for the analyses of glucose, ethanol, glycerol and total sugars. All experiments and analyses were carried out in



duplicate and results are reported with error bars and intervals representing two standard deviations.

## 2.6. Economic analysis

The investment cost 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<sub>m</sub> is 2.4 for 304 stainless steel and V is volume (gallons) [16]. 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 [17]:

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

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 [18], where FC is the cost of feedstock (\$/tonnes), Y is product yield (m<sup>3</sup>/tonne), ACE is the annual capital expenditure (\$/m<sup>3</sup>), OC is the operation cost (\$/m<sup>3</sup>), Y<sub>e</sub> is the electricity yield (kWh/m<sup>3</sup>) and EC is electricity credit (\$/kWh).

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

### 3. Results and discussion

To overcome the challenges associated with the conventional microbial bioreactors, a robust polymer composite (APCCF) was used to prepare the textile reactor in this study. A polyamide-coated PA fabric single-polymer composite (based out of PA66) was prepared in the study to address the current issues surrounding the PA-coated fabric, such as the recyclability, the adhesion between the coating and the fabrics. This was achieved by applying the PA66 solution to the polyamide fabric by means of 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 polyamide layer (the coating) and a polyamide textile fabric encompassing the most common type of aliphatic polyamide (PA66) was obtained, which form the base material for the APCCF bioreactor.

#### 3.1. Material development

Mechanical stability of the material used for constructing the bioreactor is generally of high importance [5]. Both stainless steel and concrete, that are conventional being used for the bioreactor construction, has got tremendously higher tensile strength than any available polymer. Hence the fabric based bioreactor possess 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. Polyamide generally contains amide groups that are

prominent acceptor/donator in the hydrogen-bonding [19, 20] which establishes strong intermolecular interactions. However, PVC by nature does not have strong intermolecular interaction, therefore, more susceptible to fast-breaking. Hence, the APCCF could be more robust, resulting an extended lifetime for the APCCF bioreactor material.

In the ageing test, the APCCF as well as the PVCCF were put in six different organic solvents which are the most common produced ingredients in the microbial processes [21]. According to the results (Table 1), in all of them, both APCCF and PVCCF were affected in the form of declining in mechanical properties; however, in all cases, the decrease in tensile value for the APCCF were lower than the one for the PVCCF. Starting from acetic acid, which is the second strongest unmodified organic acid (after formic acid), the polyamide chain was busy interacting with acetic acid molecules. According to Chen. *et. al.*, [22] there is an interaction between acids and polyamide 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 a better hydrogen bonding donor/acceptor exists in the vicinity of the surface polyamide chain, the amide groups prefer them and loosen the previous interaction with the inner polyamide chains. In this case, acetic acid is a better hydrogen bonding acceptor (due to having partially negative charge on the oxygen in the carbonyl) and a better hydrogen bonding donator from the acidic hydrogen. Apart from this interaction, as polyamide is a base by nature, there is another interaction in the form of acid/base interaction. Both these two interactions decrease the internal chains (from the surface towards the bulk of the polymer) which leads to decrease the crystallinity of the polymer which in turn decreases the tensile 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). Furthermore, the longer aliphatic chain decreases the mobility of the molecule and create a bigger repulsion between the butyric acid molecule and the polyamide chain which leads to less interaction between them [23]. Less interaction between polyamide and butyric acid means that more intramolecular interactions will remain, hence, the crystallinity will be changed less. It can be confirmed with the tensile 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 polyamide. That is the reason of lower measured value for lactic acid than acetic acid in tensile testing. The values for ethanol and glycerol are reasonable with the above proposal, but for acetone, which has less hydrogen bonding ability compared to all other five solvents, the decrease in the tensile 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 polyamide which needs to be elaborated in a separate study.

PVC is also affected in protic and polar solvents [24]. The reason of more decrease in tensile value for PVCCF 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. In addition, PVC in nature is a more amorphous polymer compared to polyamide [25, 26] which makes it more susceptible towards surrounding chemicals/medium.

Figure 2 shows the TGA results for the un-aged samples and the samples aged in six different solvents. Similar to the above proposal for the tensile testing, in all of the cases there is a decrease in 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 PVCCF, meaning that APCCF has superior thermal stability. Though the textile bioreactor will never experience that high temperatures (e.g. 300-400 °C), having higher ODT value (both in un-aged and aged samples) will give a better long-term stability to the APCCF [27]. From the tensile testing and TGA results, both in the un-aged sample and the aged samples in different medium –which the material of construction of the reactor will meet most– we can conclude that APCCF is a better candidate for making textile reactor than PVCCF.

Polyamide 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 [28], in general, polyamides presents a good conciliation between toughness and strength with 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 fermenter. 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 demonstrate the cross-sectional morphology of the two coated fabrics. One can observe that only a few of the filaments in the PVCCF are attached to the coating, while in the APCCF, almost all of the 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 [29]. If the adhesion is not good enough, the coating will be detached from the fabric after a certain time, called delamination [30]. In our case, the adhesion is much enough for the first-row filaments to be fused to each other. The filaments not only are adhered to the coating but also are fused to each other making the coating stronger.

Figure 4 shows the comparative density of the PVCCF and APCCF. As PVCCF is composed of two main rather heavy ingredients (compared to other conventional polymers) [31]: PVC and polyester which both are heavier (in volume/mass unit) than that of polyamide –the sole ingredient of the APCCF, resulting 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 material of construction of the bioreactor would be less than the cost for the PVCCF one.

As the polyamide chains contains amide groups (a weak organic base), they are not susceptible to mild acidic conditions (up to  $\text{pH} > 3$ ), 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 easily soluble unlike polyamides, hence posing potential challenges during the production process. Another excellent property of polyamide 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 relatively short time) and also at moderate/low temperatures for a longer exposure time. In this regard, the use of material such as polyamide 66, with 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. polyamide 66) that are 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 starch based process) or vinasse has been previously studied in conventional bioreactors [14, 15]. Comparable results were obtained from the present study using 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  $3.5 \pm 0.3$  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  $4.9 \pm 0.6$  g/L was observed at the cultivation time of 36 h with 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  $8.5 \pm 0.7$  g/L of dry weight fungal biomass. The higher fungal biomass production in vinasse, could be attributed to the presence of essential mineral components present in it, that support prolific fungal growth as observed in previous study [15]. 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 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%. Detailed results on the rheological aspects of the fungal cultivation in the APCCF bioreactor will be published in a follow-up article.

### 3.3. 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 were estimated using equation 1 and 2, and they are shown in Table 2. Similarly, the procurement cost different textile bioreactor volumes are also shown in Table 2. It can be observed from the table 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.

The estimated operation and investment cost of a stainless steel reactor is 1.7 times of its procurement cost after it has been installed [16], while that for a fabric bioreactor is 1.5 times of its procurement cost for a 15 year period [32]. This contributes to the annual production cost



as shown in equation 3. Assuming the production facility requires a 500-m<sup>3</sup> bioreactor for the producing of the desired product, and the capital expenditure is depreciated using straight line depreciation for 15 years. The developed bioreactor would contribute \$7,700/m<sup>3</sup>/year to the annual production cost, while the stainless-steel bioreactor would contribute \$33,333/m<sup>3</sup>/year to the annual production cost. If 5,000 m<sup>3</sup> of feedstock is processed in a year, using the developed bioreactor would lead to a reduction of the annual production cost by \$128,000,000.

#### **4. Conclusion**

A textile bioreactor prepared using recycled or waste fabric/textile, is introduced in this study. The bioreactor was made of all-polyamide (polyamide 66) composite coated-fabric (APCCF). The tensile testing, density measurements and thermal stability analysis (TGA) showed that the APCCF has superior characteristics than the PVCCF; hence, it is a better candidate for being the material of construction of the textile bioreactor. Introduction of the APCCF bioreactor to the conventional ethanol industry was achieved using filamentous fungi cultivation for generating value added products using the fabric bioreactor. The fungal fermentation and economic analysis of fabric bioreactor showed comparative results with conventional bioreactors. In an environmental perspective, the use of single-polymer composite material (i.e. polyamide 66) that are recycled from the textile industry presents the opportunity for making the fabric based reactor an environmentally sustainable product.

#### **5. Acknowledgments**

The authors would like to acknowledge FOV Fabrics AB, 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.

## References

1. Wilson, D.G., *Energy supplies and future engines for land, sea, and air*. Journal of the Air and Waste Management Association, 2012. **62**(6): p. 607-624.
2. Arteconi, A., N.J. Hewitt, and F. Polonara, *Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems*. Applied Thermal Engineering, 2013. **51**(1-2): p. 155-165.
3. Osadolor, O.A., P.R. Lennartsson, and M.J. Taherzadeh, *Introducing Textiles as Material of Construction of Ethanol Bioreactors*. Energies, 2014. **7**(11): p. 7555-7567.
4. Palacios-Bereche, R., et al., *New alternatives for the fermentation process in the ethanol production from sugarcane: Extractive and low temperature fermentation*. Energy, 2014. **70**: p. 595-604.
5. Blakebrough, N., *Fundamentals of fermenter design*. Pure and Applied Chemistry, 1973. **36**(3): p. 305-316.
6. Osadolor, O.A., et al., *Membrane stress analysis of collapsible tanks and bioreactors*. Biochemical Engineering Journal, 2016. **114**: p. 62-69.
7. Chernukhina, A.I. and G.A. Gabrielyan, *Thermostabilization of aliphatic polyamides and fibres on their base (review)*. Khimicheskie Volokna, 1993(6): p. 30-34.
8. Jabbari, M., et al., *Novel lightweight and highly thermally insulative silica aerogel-doped poly(vinyl chloride)-coated fabric composite*. Journal of Reinforced Plastics and Composites, 2015.
9. Jabbari, M., et al., *Introducing all-polyamide composite coated fabrics: A method to produce fully recyclable single-polymer composite coated fabrics*. Journal of Applied Polymer Science, 2016. **133**(7).
10. Angelov, R.R., B.C. Georgieva, and D.B. Karashanova, *Films of recycled polyethylene terephthalate, obtained by electrospraying, for paper and textile impregnation*. Bulgarian Chemical Communications, 2016. **48**: p. 156-160.
11. Riley, K., J. Williams, and D. Waldron, *End of Life Opportunities for Textiles in the UK Healthcare Sector*. Textile Bioengineering and Informatics Symposium Proceedings, Vols 1 and 2, 2009: p. 709-717.
12. Sommers, J., et al., *Mechanical and physical properties of recycled cellulose fibre-reinforced epoxy eco-composites C3 - Advanced Materials Research*, in *Structural Integrity and Failure*. 2008: Perth, WA. p. 317-322.
13. Low, I.M., et al., *Fabrication and properties of recycled cellulose fibre-reinforced epoxy composites*. Composite Interfaces, 2009. **16**(7-9): p. 659-669.
14. Ferreira, J.A., P.R. Lennartsson, and M.J. Taherzadeh, *Production of ethanol and biomass from thin stillage by Neurospora intermedia: a pilot study for process diversification*. Engineering in Life Sciences, 2015. **15**(8): p. 751-759.
15. Nair, R.B. and M.J. Taherzadeh, *Valorization of sugar-to-ethanol process waste vinasse: A novel biorefinery approach using edible ascomycetes filamentous fungi*. Bioresource Technology, 2016. **221**: p. 469-476.
16. Couper, J.R., et al., *COSTS OF INDIVIDUAL EQUIPMENT*, in *Chemical Process Equipment*. 2005, Elsevier Inc: Amsterdam, The Netherlands. p. 663-669.
17. Mignard, D., *Correlating the chemical engineering plant cost index with macro-economic indicators*. Chemical Engineering Research and Design, 2014. **92**(2): p. 285-294.
18. Bergeron, P., *Bioethanol market forces*, in *Handbook on bioethanol: production and utilization*, C. Wyman, Editor. 1996, CRC press. p. 61-88.
19. Vinken, E., et al., *Influence of superheated water on the hydrogen bonding and crystallography of piperazine-based (Co)polyamides*. Langmuir, 2009. **25**(9): p. 5294-5303.

20. Behler, K., et al. *Self-assembled multi-walled carbon nanotube coatings*. in *2007 MRS Fall Meeting*. 2008. Boston, MA.
21. Sathitsuksanoh, N., A. George, and Y.H.P. Zhang, *New lignocellulose pretreatments using cellulose solvents: A review*. *Journal of Chemical Technology and Biotechnology*, 2013. **88**(2): p. 169-180.
22. Chen, F. and W.V. Chang, *APPLICABILITY STUDY OF A NEW ACID-BASE INTERACTION-MODEL IN POLYPEPTIDES AND POLYAMIDES*. *Langmuir*, 1991. **7**(10): p. 2401-2404.
23. Carey, F.A. and R.J. Sundberg, *Advanced organic chemistry*. 2000.
24. Herrero, M., et al., *PVC modification with new functional groups. Influence of hydrogen bonds on reactivity, stiffness and specific volume*. *Polymer*, 2002. **43**(9): p. 2631-2636.
25. Bao, Y., et al., *The crystallinity of PVC and its effect on physical properties*. *International Polymer Processing*, 1996. **11**(4): p. 369-372.
26. Gilbert, M., *Importance of crystallinity in PVC*. *Progress in rubber and plastics technology*, 1993. **9**(2): p. 143-158.
27. Rathi, S. and J.B. Dahiya, *Effect on thermal behaviour of polyamide 66/clay nanocomposites with inorganic flame retardant additives*. *Indian Journal of Chemistry Section a-Inorganic Bio-Inorganic Physical Theoretical & Analytical Chemistry*, 2012. **51**(12): p. 1677-1685.
28. Buckley, R.W., *POLYMER ENHANCEMENT OF TECHNICAL TEXTILES*, in *Rapra.Review Rept. No.165; Shawbury, Rapra Technology Ltd., 2003, pp.130, 30 cms. Rapra Review Rept. No. 165, vol.14, No.9, 2003. NALOAN*. 2003.
29. Sargent, J.G., et al. *Study of selectively permeable coatings to textiles C3 - Materials Research Society Symposium Proceedings*. in *2010 MRS Fall Meeting*. 2011. Boston, MA.
30. Završnik, T., *Polyurethanes in textile coating technology*. 1984.
31. Lodi, P.C., B. De Souza Bueno, and O.M. Vilar, *The effects of weathering exposure on the physical, mechanical, and thermal properties of high-density polyethylene and poly(vinyl chloride)*. *Materials Research*, 2013. **16**(6): p. 1331-1335.
32. Rajendran, K., et al., *Experimental and economical evaluation of a novel biogas digester*. *Energy Conversion and Management*, 2013. **74**: p. 183-191.

## Tables and Figures

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

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

Table 2: Comparative procurement cost for APCCF bioreactor and 304-stainless steel reactor vessels

Reactor size (m <sup>3</sup> )	Purchase Cost of developed textile bioreactor (\$)	Purchase cost of 304 stainless steel reactor (\$)
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

## Figures

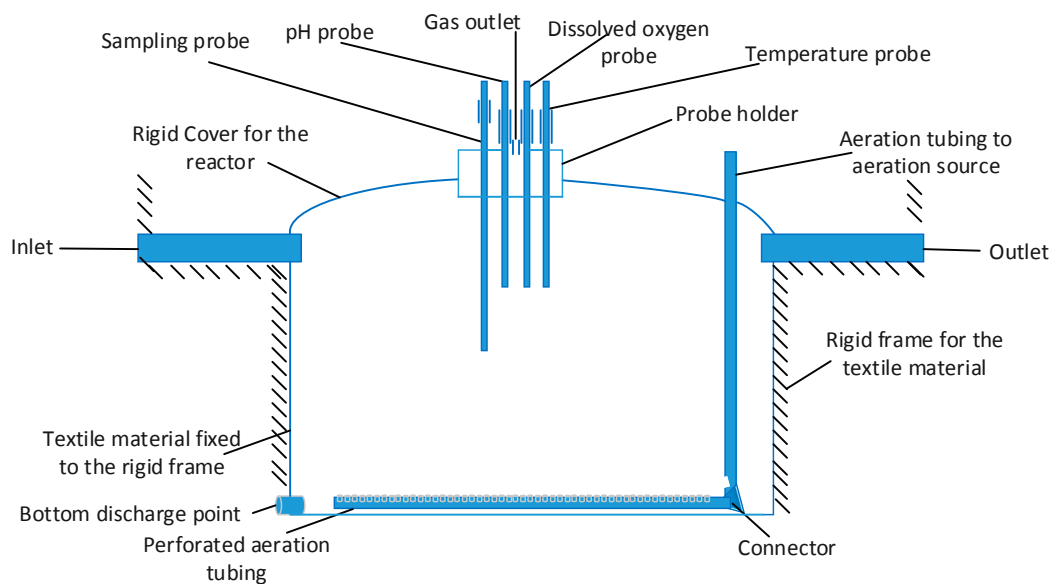


Figure 1: General schematic representation of APCCF bioreactor

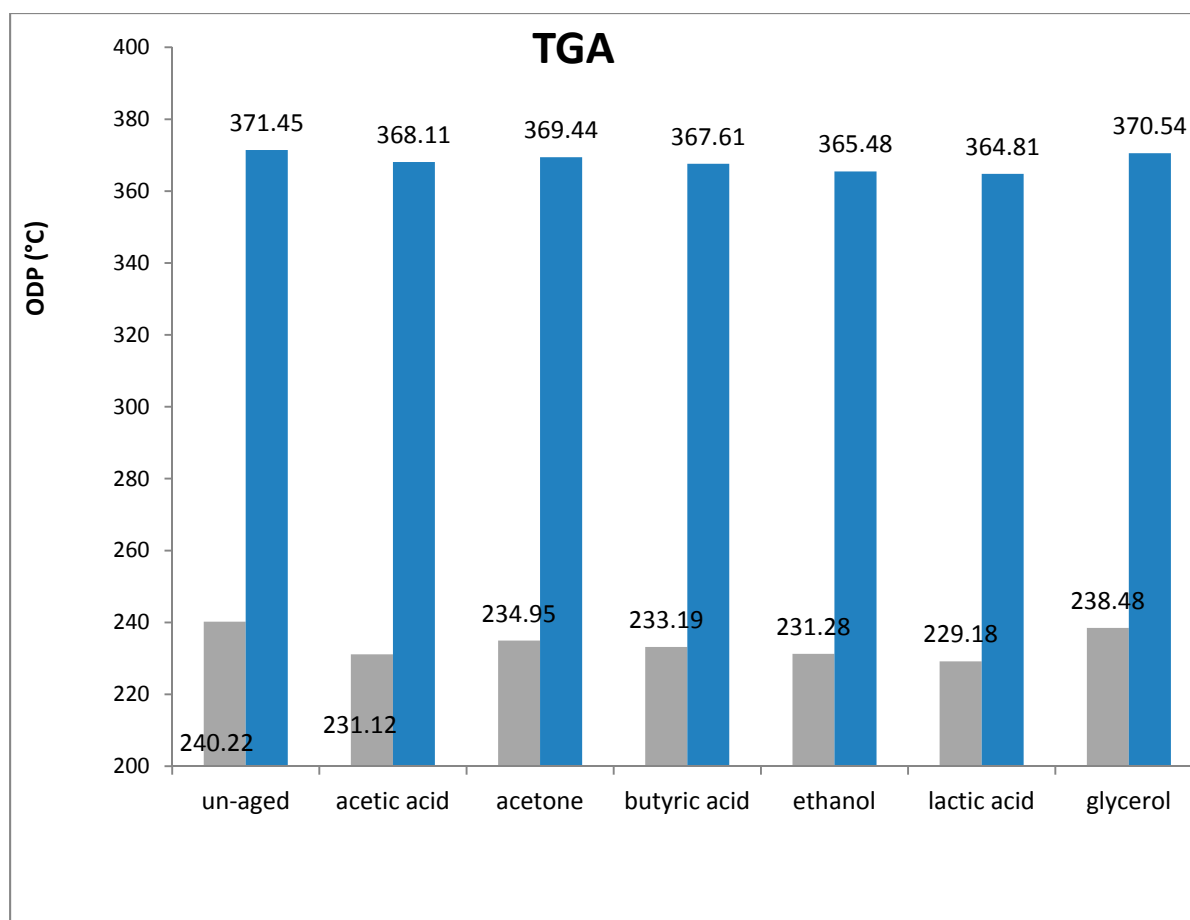


Figure 2: comparative onset decomposition temperatures for PVCCF and APCCF samples in different conditions (un-aged: before the ageing test, the rest are corresponding to ageing the samples in different mediums).

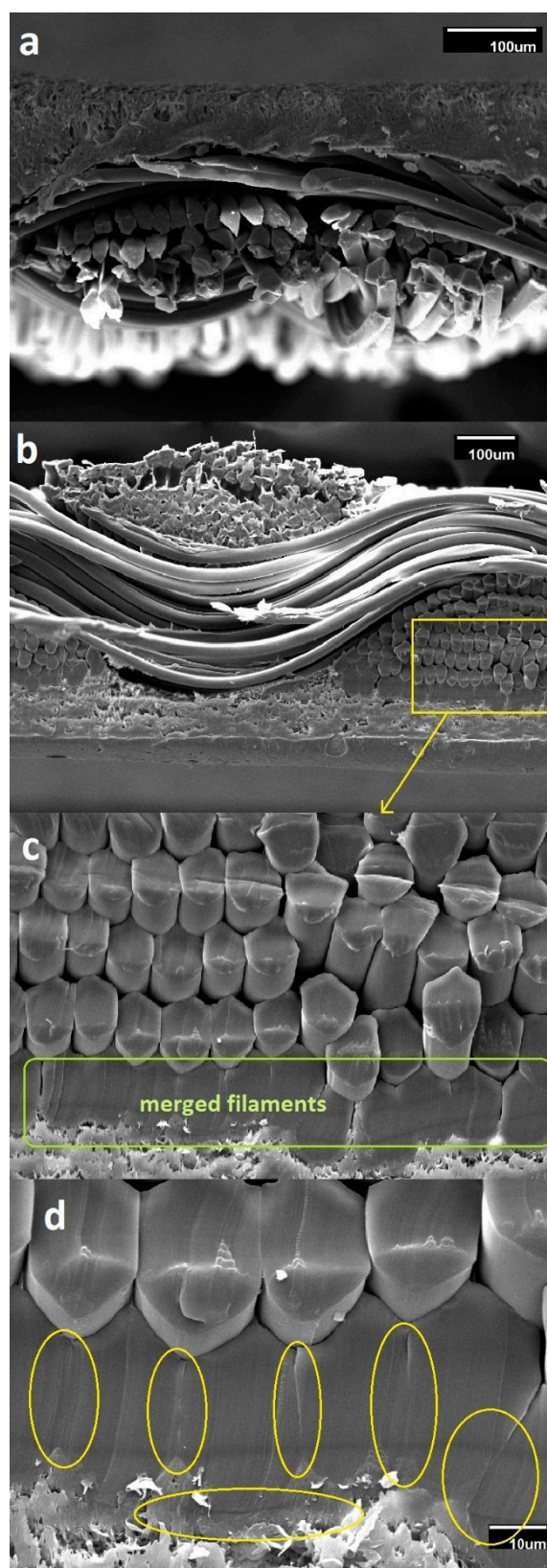


Figure 3. cross-sectional SEM picture of PVCCF (a) and APCCF (b and c). The fused parts are shown with the yellow ovals (d). It is clear that in PVCCF, the adhesion is not homogeneous and strong while in APCCF, the first row of the filaments of the PA fabric are merged together and adhered to the coating.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



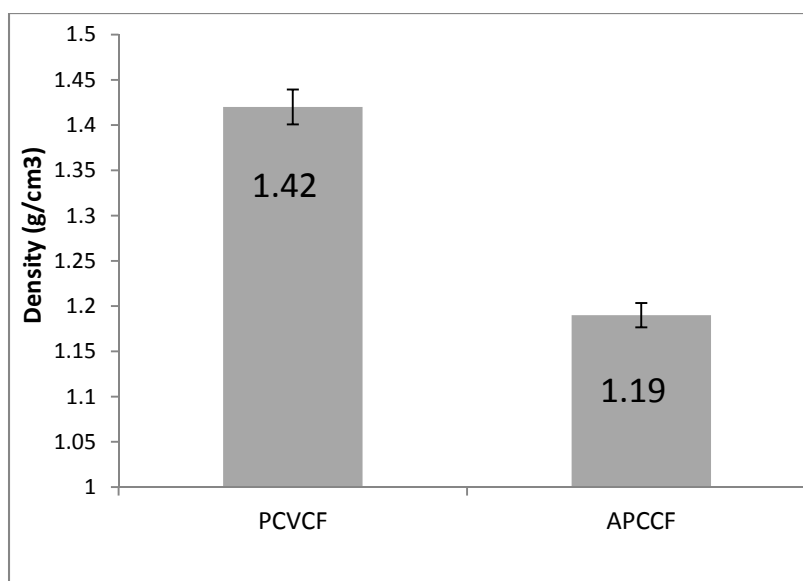


Figure 4. Comparative density of the PVCCF and APCCF. PVCCF is composed of two main ingredients: PVC and polyester which both are heavier in volume/mass unit than that of polyamide –the sole ingredient of the APCCF, resulting a lighter material.

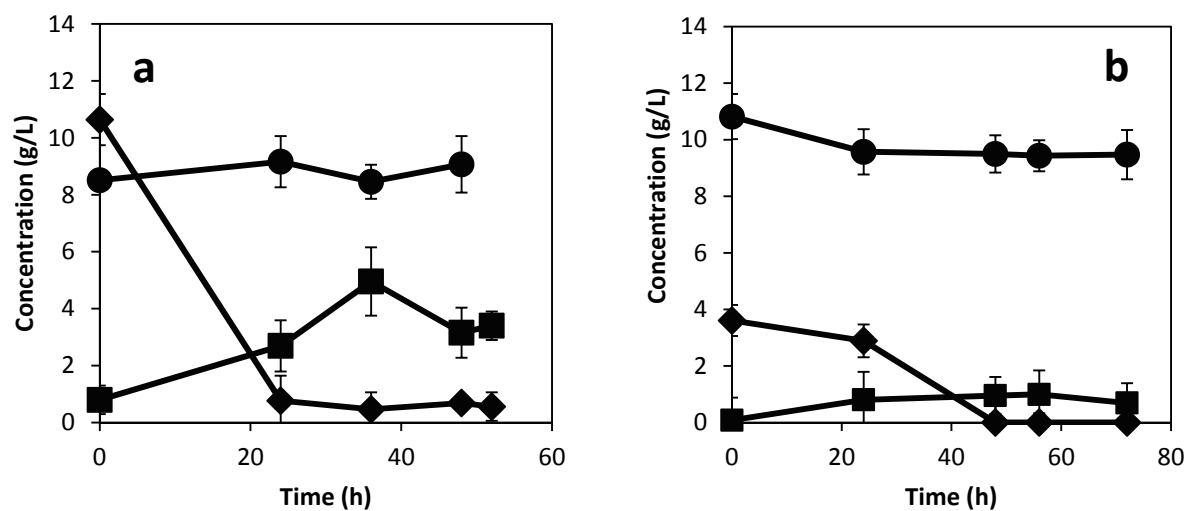


Figure 5: Fermentation of thin stillage (a) and vinase (b) in the textile bioreactor showing total fermentable sugar (◆), ethanol (■) and glycerol (●).