

A TWO-LAYER SILK FIBROIN NANOFIBROUS MATERIAL: FABRICATION, SPECIFIC PROCESS INDICATORS AND AN INVESTMENT-BASED TECHNO-ECONOMIC ASSESSMENT OF LABORATORY-SCALE PRODUCTION

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Abstract

Techno-economic assessments of electrospun materials rarely go beyond a unit-cost calculation and a margin, which can conceal whether the capital employed is recovered at all. This work fabricates a two-layer silk fibroin nanofibrous material, characterises the process through specific indicators, and then assesses it with investment criteria rather than accounting margins alone. The material is produced in two stages: a water-soluble first layer from a 16% poly(vinyl alcohol) solution, which reduces adhesion to the substrate, and a second layer from a composite of 40% silk fibroin solution and 60% poly(vinyl alcohol) solution. One production cycle converts 5 mL of solution into approximately 0.75 g of dry polymer over 0.065 m², an areal density of about 11.6 g m⁻². Separating the cost structure shows that fixed costs account for 89.6% of total cost, giving a break-even point of 529 units per month, that is 89.9% of installed capacity, and a financial safety margin of only 10.1%. Investment analysis is markedly less favourable than the accounting margin of 10.1% suggests: the simple payback period is 26.5 years against a 10-year equipment life, the cash payback period including the depreciation add-back is 7.3 years, and the net present value at a 10% discount rate over ten years is negative. Doubling throughput, which is achievable by fitting a multi-emitter head without additional machine capital, changes the outcome decisively, and the maximum additional capital expenditure that such a modification could justify is quantified. An occupational-risk assessment using a probability × severity matrix and an environmental-aspect analysis complete the evaluation.

Keywords: Silk fibroin; two-layer nanofibrous material; areal density; cost structure; break-even analysis; net present value; payback period; occupational risk; environmental aspects.



Introduction

Non-woven nanofibrous materials obtained by electrospinning are increasingly used in medicine, bioengineering and cosmetology. Their high porosity, large specific surface area and small fibre diameter allow them to be applied as wound dressings, cell substrates, drug-delivery systems and cosmetic masks [1, 2].

In practice, removing the nanofibrous material from the substrate without damage remains a distinct problem. In earlier stages of this work it was established that material obtained from a spinning solution containing silk fibroin adhered strongly to the substrate. To eliminate this defect a two-layer material design was proposed, in which the first layer, in direct contact with the substrate, is formed from water-soluble poly(vinyl alcohol).

Recommending a new material for production requires that its economic indicators be calculated alongside its technical characteristics. In existing work the economic evaluation of nanofibrous materials is usually confined to a unit-cost calculation and a margin on cost. That is a weak test. A margin expresses the relation between price and cost within a single period; it says nothing about whether the capital invested in the equipment is recovered over its life, and a process can show a positive accounting margin while destroying value. Separating fixed from variable costs, locating the break-even point, and applying discounted investment criteria are what determine whether a technology should be implemented.

The novelty of this work lies in computing specific process indicators — dry-polymer yield per cycle and areal density of the coating — for the two-layer material, and in assessing the technology by investment criteria (payback period, net present value, elasticity of unit cost with respect to volume) rather than by accounting margin alone, thereby identifying the scale at which the technology becomes viable.

The aim of the work is to develop a two-layer nanofibrous material, to characterise it, and to assess its technical and economic effectiveness on the basis of break-even and investment analysis.

2. Materials and methods

2.1. Fabrication

The nanofibrous material was produced on a Fluidnatek LE-50 laboratory electrospinning system in two stages. First, a 16% solution of poly(vinyl alcohol) was applied to the substrate for 30 min, which forms a water-soluble layer and reduces the probability of the subsequent layers penetrating into the substrate. In the second stage the final composite spinning solution — 40% fibroin solution (0.2 g of fibroin per 5.5 g of solvent) and 60% of the 16% poly(vinyl alcohol) solution, with a total polymer content of 11.0 wt% and a density of 1.235 g cm^{-3} — was applied for 30 min. The regime parameters of both stages are given in Table 1.

Table 1. Regime for producing the two-layer nanofibrous material.

Parameter	Value
Emitter-to-collector distance	10 cm
Emitter voltage	+29 kV
Collector voltage	−9 kV
Spinning-solution feed rate	5 mL h ^{−1}
Collector rotation speed	200 min ^{−1}
Deposition time per layer	30 min
Relative humidity	40%
Laboratory temperature	20–22 °C
Substrate	polyester lining fabric, 34 × 19 cm

Polyester lining fabric was selected as the substrate. Experimental studies showed that the resulting materials adhere less strongly to polyester fabric than to black paper; in addition, the use of fabric reduces waste through more efficient use of the surface area. The principal fabric characteristics are: plain weave, areal density 57.4 g m^{−2}, thread density 400 threads per 10 cm in warp and weft, and linear density of the yarn 9.2 tex.

2.2. Characterisation and specific indicators

The structure of the specimen was visualised with a LEO 1420 scanning electron microscope (Carl Zeiss, Germany) at 15000× magnification. To assess the specific indicators of the process, the mass of dry polymer formed in one cycle was computed as

$$\dot{m} = V \cdot \rho \cdot w, \quad (1)$$

where V is the solution volume (cm³), ρ its density (g cm^{−3}) and w the mass fraction of polymer. The areal density of the coating was determined as

$$\rho_s = \Sigma \dot{m} / A, \quad (2)$$

where A is the coated area (m²).

2.3. Economic analysis

Economic indicators were computed by the cost method. For the break-even analysis the monthly costs were separated into fixed (wages, social contributions, general production costs, depreciation) and variable (raw materials, energy, distribution costs) components. The break-even point was computed as

$$Q_{be} = F_{fix} / (P - v_{var}), \quad (3)$$

where F_{fix} is the monthly fixed cost, P the wholesale unit price and v_{var} the variable cost per unit. The financial safety margin was taken as $(Q_{act} - Q_{be})/Q_{act}$.

For the investment assessment the annual net cash flow was taken as the annual profit with depreciation added back, since depreciation is a non-cash charge. The simple payback period was computed as the ratio of capital expenditure to annual profit and the cash payback period

as the ratio of capital expenditure to annual net cash flow. The net present value over the equipment life was computed as

$$NPV = -C_0 + \sum CF_t / (1 + r)^t, \quad (4)$$

with C_0 the capital expenditure, CF_t the annual net cash flow, r the discount rate (taken as 10%) and t the year, summed over the ten-year equipment life. The elasticity of unit cost with respect to production volume was computed as

$$E = -(F_{fix}/Q) / (F_{fix}/Q + v_{var}). \quad (5)$$

All monetary values are expressed in conventional monetary units (c.u.) at the price level and exchange rate of the experimental period.

3. Results

3.1. Structure of the material

Under the parameters of Table 1 the electrospinning process was stable and two-layer nanomaterial specimens were obtained. A micrograph of the upper layer is shown in Fig. 1.

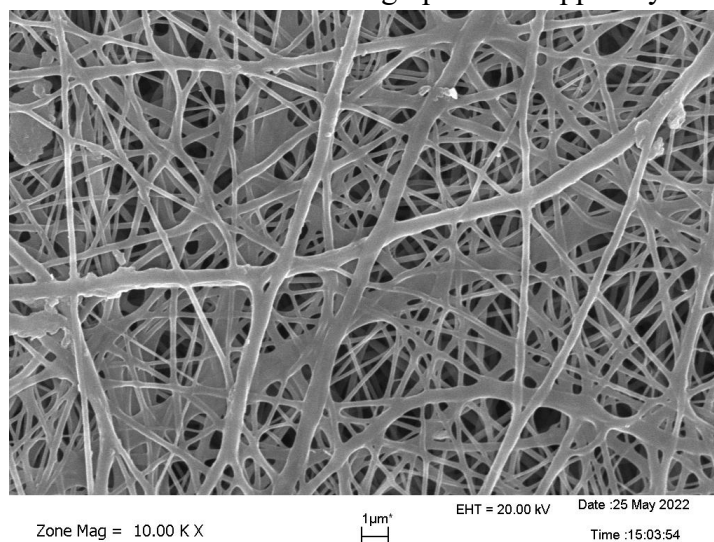


Fig. 1. Structure of the upper layer of the nanomaterial obtained, at 15000× magnification.

Analysis of the micrographs shows that the substantial quantity of calcium chloride affects the morphology of individual fibres and produces thickenings that are probably microgranules of the salt. Overall the surface of the material is homogeneous and free of significant defects.

3.2. Specific process indicators

Table 2 gives the specific indicators computed from Eqs. (1) and (2). The density of the 16% poly(vinyl alcohol) solution was taken as 1.03 g cm^{-3} .

Table 2. Specific indicators of one production cycle.

Indicator	Layer 1 (16% PVA)	Layer 2 (composite)	Total
Solution volume, mL	2.5	2.5	5.0
Solution density, g cm ⁻³	1.03*	1.235	–
Polymer mass fraction, %	16.0	11.0	–
Dry polymer mass, g	0.41	0.34	0.75
Coated area, m ²	0.0646	0.0646	0.0646
Areal density, g m ⁻²	6.4	5.3	11.6

* assumed value; not measured directly.

The production shop operates in two shifts, one operator being assigned to the equipment in each shift; a shift lasts 8 h, of which 7 h are devoted to the process itself and one hour to preparatory work. With an average of 21 working days per month the production capacity is 588 units per month, that is 2 units per machine-hour (spinning itself occupies one hour, after which drying, removal from the collector and cutting are carried out).

3.3. Cost structure

Table 3 gives the raw-material balance per 100 units of finished product and Table 4 the cost calculation with the costs classified as fixed or variable.

Table 3. Raw-material balance per 100 units of finished product.

Raw material	Consumption	Price per kg (L), c.u.	Cost, c.u.
Poly(vinyl alcohol)	16 g	21.40	0.34
Silk fibroin	1 g	9.03	0.01
Sodium carbonate	0.06 g	1.20	0.00007
Laundry soap	0.08 g	5.00	0.0004
Calcium chloride	23.3 g	15.23	0.36
Ethanol	14.6 g	14.15	0.21
Distilled water	17.1 g	0.52	0.01
Polyester fabric	92.5 g	58.10	5.35
Transport and procurement	–	–	0.13
Total	164.64 g	–	6.41

Table 4. Cost calculation and classification of costs.

No.	Cost element	Type	Per month, c.u.	Per unit, c.u.	Share, %
1	Raw materials and main materials	variable	37.70	0.06	1.11
2	Fuel and energy for the process	variable	282.24	0.48	8.32
3	Wages of production workers	fixed	1100.00	1.87	32.43
4	Social security contributions	fixed	385.00	0.65	11.35
5	General production costs	fixed	647.90	1.10	19.10
6	Depreciation	fixed	905.52	1.54	26.70
7	Production cost	–	3358.36	5.71	99.01
8	Distribution costs	variable	33.58	0.06	0.99
9	Total cost	–	3391.94	5.77	100.00

From this classification the fixed costs amount to 3038.42 c.u. per month, that is 89.6% of the total cost, while the variable costs are 353.52 c.u. per month, or 0.60 c.u. per unit.

3.4. Break-even analysis

The free selling price of a unit is formed from the total cost, the planned profit and value-added tax, and amounts to 7.62 c.u.; the wholesale price net of tax is 6.35 c.u. The profit from sales is 341.86 c.u. per month and the margin on cost is 10.1%.

The contribution margin per unit is $6.35 - 0.60 = 5.75$ c.u., whence from Eq. (3)

$$Q_{be} = 3038.42 / 5.75 \approx 529 \text{ units per month.}$$

This corresponds to 89.9% of the installed capacity, so that the financial safety margin is only 10.1%. Table 5 shows the dependence of unit cost on production volume with fixed costs held constant.

Table 5. Unit cost as a function of production volume (fixed costs assumed unchanged).

Volume, units per month	588	800	1200	1800	2400
Unit cost, c.u.	5.77	4.40	3.13	2.29	1.87
Relative to capacity, %	100	136	204	306	408

The elasticity of unit cost with respect to volume computed from Eq. (5) is -0.90 at the design volume and -0.81 at 1200 units per month: a 1% increase in output reduces unit cost by approximately 0.9%, which is close to the theoretical maximum leverage available in a fixed-cost-dominated operation.

3.5. Investment assessment

The cost of the equipment including transport and installation was 41 050 euro, equivalent to 108 536 c.u.; its useful life is 10 years and depreciation is computed on a straight-line basis at an annual rate of 10%.

The annual profit is $341.86 \times 12 = 4102$ c.u., so the simple payback period is $108\,536 / 4102 = 26.5$ years — more than two and a half times the useful life of the equipment. Adding back

depreciation, which is a non-cash charge, gives a monthly net cash flow of $341.86 + 905.52 = 1247.38$ c.u. and an annual cash flow of 14 969 c.u., so the cash payback period is 7.3 years. Applying Eq. (4) with a 10% discount rate over the ten-year life gives $NPV = -16\,561$ c.u. Table 6 summarises these indicators together with those for higher production volumes.

Table 6. Investment indicators as a function of production volume.

Volume, units per month	Monthly net cash flow, c.u.	Cash payback period, years	NPV at 10% over 10 years, c.u.
588 (design capacity)	1247	7.3	-16 561
1200	4766	1.9	+242 877
2400	11 665	0.8	+751 558

Computed on the assumption that fixed costs and capital expenditure remain unchanged as volume increases, which corresponds to raising throughput by fitting a multi-emitter spinning head to the existing machine.

3.6. Occupational risk and environmental aspects

Occupational risk was assessed using the standard product form

$$R = P \times S, \quad (6)$$

where P is the probability of occurrence (1–5 points) and S the severity of the consequences (1–5 points). Risks are classified as low ($R < 6$), medium ($6 \leq R \leq 12$) and high ($R > 12$); low risks are regarded as acceptable and controllable by existing measures, while medium and high risks are regarded as unacceptable and require the development of mitigating measures.

Measurement of the working-environment factors in the laboratory gave values within the hygienic norms in every case: noise 58 dBA against a norm of 60 dBA; non-ionising electromagnetic field 20 V m^{-1} against 25 V m^{-1} ; air temperature 23–24 °C in the cold season and 23–26 °C in the warm season against norms of 22–24 °C and 23–25 °C; relative humidity 40–60%; air velocity 0.1 m s^{-1} ; and thermal radiation 35 W m^{-2} against a norm of 90 W m^{-2} . The hazards specific to the installation are the rotating collector and the presence of high voltage; protection is provided by interlocks, earthing of the equipment, enclosure of live parts and warning signage, and the premises fall in explosion and fire category B with fire-resistance class II.

The environmental aspects of the process are limited. The only process emission is the evaporation of the spinning solvent, controlled by extraction through filters; no industrial or ventilation discharges to the atmosphere are recorded and no technological operations generate static-electricity accumulation beyond that controlled by earthing. Solid wastes are of hazard classes 3 and 4 and are directed to recovery rather than disposal, with the exception of worn workwear.



4. Discussion

4.1. Material properties and intended application

The presence of salt particles in individual fibres is in this case an advantage rather than a defect. Calcium chloride is widely used in medicine and exerts haemostatic, detoxifying, antiallergic and anti-inflammatory effects on the body and reduces capillary permeability [3]. In cosmetology it is used as a mechanical and chemical peeling agent. Silk fibroin in turn acts as a moisture-retaining agent for any skin type: its principal amino acid, glycine, is readily absorbed by the skin because of its low molecular weight and accelerates the metabolism of skin cells; fibroin also has antioxidant properties [4, 5].

The computed areal density of about 11.6 g m^{-2} places the material among ultralight coatings in the classification of non-woven fabrics. This value is marginal for use as a free-standing layer and indicates that the material is better suited to use as the active layer of a cosmetic mask or dressing in combination with a carrier substrate.

4.2. Why the accounting margin is a misleading indicator

The principal result of the economic analysis is the contrast between the accounting and the investment views of the same operation. On the accounting view the process is modestly profitable: the margin on cost is 10.1% and the selling price of 7.62 c.u. sits in the lower part of the 3.93–204 c.u. range of skin-care scrubs and peels, so the product is price-competitive.

On the investment view the same operation does not recover its capital. The simple payback period of 26.5 years exceeds the 10-year equipment life by a factor of 2.65, and even the cash payback period of 7.3 years, which credits the depreciation add-back, leaves only 2.7 years of useful life to generate a return. The net present value at a 10% discount rate is negative, at –16 561 c.u. In other words, at the design volume of 588 units per month the technology is profitable in the accounting sense and value-destroying in the investment sense. Reporting the margin alone would conceal this entirely.

The reason is visible in the cost structure. Fixed costs constitute 89.6% of total cost and raw materials only 1.11%. A structure of this kind is characteristic of laboratory-scale production and has two consequences. First, the break-even point lies at 89.9% of capacity, so that a fall in output of just over 10% takes the operation into loss — a very high operating risk. Second, precisely this structure creates a powerful reserve of scale economy.

4.3. The scale at which the technology becomes viable

Table 6 locates that scale. Doubling output to 1200 units per month turns the net present value from –16 561 to +242 877 c.u. and shortens the cash payback period from 7.3 to 1.9 years; a fourfold increase shortens it to less than a year. The elasticity of –0.90 quantifies the same effect differently: almost the whole of any volume increase is converted into unit-cost reduction.

This result also bounds the investment that may rationally be made to obtain the additional throughput. Since the net present value at 1200 units per month is +242 877 c.u. on the assumption of unchanged capital expenditure, any modification that doubles throughput and costs less than that amount is justified. A multi-emitter spinning head, or an emitter scanning

stage combined with a wider collector, falls far below this bound, which makes the direction of development unambiguous.

The conclusion connects directly with the resource analysis of the same technology, in which the fibroin consumption of 0.01 g per unit and a raw-material share below 1.2% of cost showed that silk waste is not the limiting factor. Both analyses point to the same constraint: the throughput of the electrospinning process itself. Effort directed at cheaper raw material would move 1.11% of the cost base; effort directed at throughput moves 89.6% of it.

4.4. Limitations

Four limitations should be stated. First, the economic indicators rest on the price level and exchange rate of the experimental period; implementing the technology under other conditions requires the prices of raw materials, the level of wages and tax rates to be recomputed, although the proportions within the cost structure are qualitatively robust. Second, the dry-polymer yield and areal density were obtained by calculation and not measured gravimetrically, and the density of the 16% poly(vinyl alcohol) solution was an assumed value. Third, the source data state that four units are obtained in a one-hour cycle while the monthly capacity is 588 units; these two figures have been reconciled here through the time taken by preparatory and finishing operations, but confirmation of the productivity balance by direct time study is recommended. Fourth, the scale analysis of Table 6 assumes that fixed costs and capital expenditure remain unchanged as throughput increases; a multi-emitter head would in practice add some capital cost and possibly some maintenance cost, which the bound derived in Section 4.3 accommodates but does not quantify.

5. Conclusions

A two-layer nanofibrous material was developed in order to reduce adhesion to the substrate: the first layer is formed from a 16% poly(vinyl alcohol) solution and the second from a composite of 40% fibroin solution and 60% poly(vinyl alcohol) solution, each deposited for 30 min. The surface of the material is homogeneous with few defects, and the calcium chloride particles present in the fibres allow it to be used in medicine and cosmetology.

Specific process indicators were computed: one cycle converts 5 mL of solution into approximately 0.75 g of dry polymer over 0.065 m², giving an areal density of about 11.6 g m⁻².

Separating the cost structure shows that fixed costs constitute 89.6% of total cost and raw materials only 1.11%. The break-even point is 529 units per month, that is 89.9% of capacity, and the financial safety margin is only 10.1%.

Investment analysis contradicts the accounting view: although the margin on cost is 10.1% and the product is price-competitive, the simple payback period is 26.5 years against a 10-year equipment life, the cash payback period is 7.3 years, and the net present value at a 10% discount rate is -16 561 c.u. At the design volume the technology is therefore profitable in the accounting sense but value-destroying in the investment sense.

Doubling throughput reverses this: the net present value becomes +242 877 c.u. and the cash payback period falls to 1.9 years. This also bounds the capital that may rationally be spent to

obtain the additional throughput, and identifies multi-emitter spinning heads as the priority direction of development. Occupational-environment factors were found to lie within hygienic norms and the environmental aspects of the process to be limited to controlled solvent evaporation and recoverable solid waste.

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