



Investigating environmental burdens and benefits of biologically inspired self-cleaning surfaces

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ABSTRACT

Biologically inspired sustainable engineering seeks to abstract ideas from nature and apply them in engineering to improve environmental performance. “Self-cleaning” surfaces, which repel water and aid in contaminant removal, stand as one example. While statements touting their benefits appear in the literature, limited scientific data exists. This article contains a life cycle inventory that quantifies the potential environmental benefits and burdens associated with using these surfaces. While use phase benefits are apparent, production burdens can outweigh them when compared with other cleaning methods. This outcome suggests the need for a more thoughtful and deliberate use of bio-inspiration in sustainable engineering.

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1. Biologically inspired design and sustainability

Biologically inspired design is used as an approach to environmentally sustainable engineering. In a biologically inspired approach, a designer abstracts ideas and principles from nature. The designer then uses the abstracted principle or idea with the goal of producing an environmentally superior design. Self-cleaning surface technology inspired by observations of organism surfaces is one example. Given life’s success and long history of persistence, it is logical to turn to the living world for guidance when attempting to engineer sustainable products, processes and systems.

However, a recent assessment of biologically inspired products suggested that imitating a few of an organism’s features or functions may not guarantee environmentally preferable outcomes [1]. In the case of self-cleaning surfaces, many researchers responsible for the technology claim potential environmental benefits based on expected reductions in cleaning intensity [2]. However, little scientific data exists in the open literature which quantifies the benefits of use or the burdens of production.

To fill this data deficit, this work inventories the life cycle of one means of producing self-cleaning surfaces and compares its environmental performance with standard industrial cleaning techniques. It seeks to answer the question: do environmental

benefits in the use phase outweigh environmental costs associated with other life cycle phases? The work attempts to use this case as a lens to examine the broader question of biological inspiration’s value in sustainable engineering.

2. Self-cleaning surfaces

2.1. Biological inspiration and benefits

To appreciate the potential benefits of self-cleaning surfaces, one must understand the biological phenomenon. Micro- and nano-scale surface roughness features combine with hydrophobic surface chemistries to generate the self-cleaning phenomenon. These changes create highly hydrophobic surfaces which cause water to “bead,” as shown in Fig. 1.

The beaded water quickly leaves the surface of an organism, taking contaminants with it. The self-cleaning ability is called the “Lotus Effect,” in honor of the first plant observed to exhibit it [3].

Interestingly, many other organisms use hydrophobic, micro/nano-rough surfaces to achieve self-cleaning. In a study of 200 plant species, the majority proved highly hydrophobic [4]. Wing surfaces of many insect species possess hydrophobic properties and self-clean [5]. Gecko feet exhibit self-cleaning properties which surprisingly help maintain the adhesive abilities of their feet [6]. Even higher organisms such as Pilot whales have micro- and nano-scale surface features [7]. These skin features prevent biofouling from accumulating and affecting the whale’s hydrodynamics.

Soiling and cleaning an aluminum surface coated with a hydrophobic film meant to mimic the “Lotus Effect” illustrates the phenomenon (see Fig. 2).

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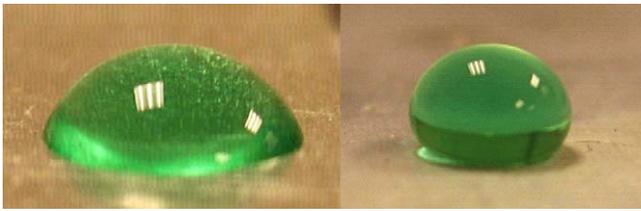


Fig. 1. Water drop on aluminum: left—untreated, right—self-cleaning.

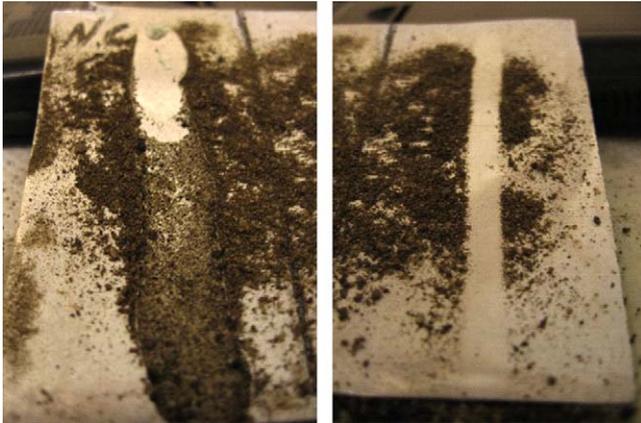


Fig. 2. Comparison of cleaning soiled aluminum: left—untreated, right—self-cleaning.

On the uncoated side, the water runs over the contaminants, while on the self-cleaning side, the water removes contaminants as it rolls off the surface. Water easily removes contaminants from the self-cleaning side, but the uncoated side may need more intensive cleaning. By showing the difference in required cleaning resources, this simple demonstration illustrates that self-cleaning surfaces hold potential environmental benefits and could replace more energy and material intensive industrial cleaning methods.

2.2. Physics of hydrophobicity

The previous section illustrated the benefits of self-cleaning and identified surface chemistry and structure as influential factors. This section connects self-cleaning with these factors through an introduction to the physics of hydrophobicity. One measures a surface's hydrophobicity or hydrophilicity in terms of the contact angle which water forms with it. The measurement of a contact angle is shown in Fig. 3.

Hydrophilic surfaces possess water contact angles less than 90° ; water wets them. Hydrophobic, or non-wetting, surfaces display contact angles exceeding 90° . When contact angles surpass 150° , one classifies the surface as superhydrophobic.

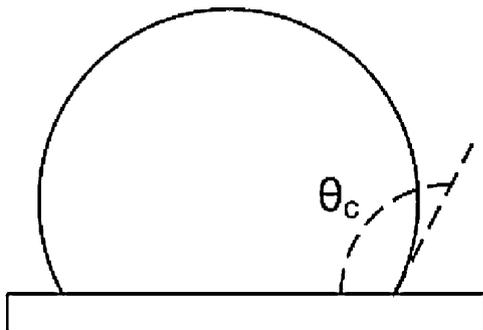


Fig. 3. Measurement of contact angle.

Young proposed a model for the contact angle on a flat surface, in thermodynamic equilibrium where σ_{sf} , σ_{sl} and σ_{lf} are the solid–fluid, solid–liquid and liquid–fluid interfacial tensions, respectively (see Eq. (1)).

$$\cos \theta_y = \frac{\sigma_{sf} - \sigma_{sl}}{\sigma_{lf}} \quad (1)$$

Wenzel [8] updated the model for the rough surfaces (see Eq. (2)).

$$\cos \theta_c = r \cos \theta_y \quad (2)$$

In Wenzel's model, θ_c is the apparent contact angle, and r is the roughness factor, a ratio of the actual surface area to the geometric surface area (always greater than 1). Increasing the roughness of an already hydrophobic surface increases its hydrophobicity, while increasing the roughness of a hydrophilic surface makes it more hydrophilic.

Cassie and Baxter [9] expanded the previous model for rough, porous surfaces using Eq. (3).

$$\cos \theta_c = \phi_s \cos \theta_y + \phi_a \quad (3)$$

where ϕ_s is the area fraction of liquid–solid contact, and ϕ_a is the area fraction of liquid–air contact. The two models treat the interface beneath a fluid droplet differently. In Wenzel's model, liquid fills the volume between surface roughness features, but in the Cassie and Baxter model, the liquid rests on top of the surface roughness, trapping air and forming a composite surface.

While falling beyond the life cycle assessment focused purview of this paper, it is important to note that a number of researchers expanded upon the work of Wenzel, Cassie and Baxter in recent years. Some investigated different small scale surface geometries [10,11]. Others investigated the energetic characteristics of such surfaces [12]. And, some even demonstrated ways of defeating self-cleaning surfaces [13]. Those with a specific interest in tribology should consult these and related works.

2.3. Methods of production

Tempted by observed benefits and armed with an understanding of the basic physics, researchers successfully recreated biologically inspired, water repellent, self-cleaning surfaces for engineering applications. They create these surfaces using one of two approaches. In the first, they coat surfaces (hydrophobic OR hydrophilic) with hydrophobic films. The second enhances an already hydrophobic material by adding surface roughness.

A review of hydrophobic film technologies [14] shows that over 50 years of research resulted in at least 21 different methods of producing films: addition of fillers, etching, plasma polymerization, plating with fluoride particles, wax solidification, anode oxidation, solution-precipitation, reaction, chemical vapor deposition, addition of sublimation material, phase separation, and molding. Many films lacked transparency and durability. Keeping surface feature size under 300 nm fixed the former problem [15], while adding titanium dioxide photocatalysts remedied the latter [16].

Among the methods of adding surface roughness to hydrophobic materials are nanostructured templates. One template process involves electrochemically structured aluminum templates pressed on polymeric sheets and heated [17]; another template method rolls an anodized, heated aluminum tube over polycarbonate [18]. Femtosecond laser pulses produced nanostructures on steel and silicon [19,20]. Carbon nanotubes coated with a water repellent chemical have also been used to produce self-cleaning surface [21,22].

3. Life cycle inventory (LCI)

3.1. Goal scope and functional unit

The study's goal is to compare the life cycle of a self-cleaning surface created using a chemical coating to conventionally cleaned surfaces. It seeks to determine whether the environmental production burdens heavily outweigh the self-cleaning surface's use phase advantages.

The scope of the study includes the materials acquisition, production, and use phases for self-cleaning surface and conventional cleaning life cycles. It incorporates the main resources consumed and emissions generated during these life cycle phases. The study emphasizes the materials used in production as well as the use phase, as these parts of the life cycle often prove dominant. Given the comparative newness of this type of surface, one should consider the work a "first order" assessment. Critical simplifying assumptions related to the modelling of each life cycle appear in the appropriate sections.

The functional unit for the examined self-cleaning surfaces is 1 m² of surface area. For conventional cleaning, the functional unit becomes the potential range of volumes needed to enclose a surface area of 1 m².

3.2. Chemical coating

3.2.1. Chemical production

The coating under assessment is produced with five chemicals [16]:

- Titanium acetylacetonate (TiO(C₅H₇O₂)₂)
- Aluminum acetylacetonate (Al(C₅H₇O₂)₃)
- Boehmite (AlOOH)
- Ethanol (C₂H₅OH)
- A water repellent agent

Life cycle data for chemicals such as titanium acetylacetonate and aluminum acetylacetonate are not readily available. So, one must trace their constituent chemicals back to components which come from natural resources or reactants found in life cycle inventory databases.

Titanium acetylacetonate is a product of the reaction of titanium oxychloride (TiOCl₂), acetylacetonone (C₅H₈O₂) and sodium carbonate (Na₂CO₃) [23]. Sodium carbonate, or soda ash, is a mined material for which life cycle data are available. Titanium oxychloride is formed in a reaction between titanium chloride (TiCl₄) and water [24]. A reaction of rutile (TiO₂), chlorine (Cl₂) and carbon produces titanium chloride [24]. Rutile is a mined material, carbon comes from mined natural resources and chlorine is produced as a co-product, along with caustic soda, from brine.

Acetylacetonone (C₅H₈O₂) is rearranged from isopropenyl acetate with a catalyst. Isopropenyl acetate forms when acetone (CH₃C(O)CH₃) and acetic anhydride ((CH₃CO)₂O) react [25]. Life cycle data are available for both acetone and acetic anhydride.

Aluminum acetylacetonate can be produced by a reaction of aluminum sulphate (Al₂(SO₄)₃*nH₂O) and acetylacetonone [26]. Life cycle data are available for aluminum sulphate, and acetylacetonone is produced as described above.

For chemicals lacking publicly available life cycle data, guidelines [27] exist for determining total resource consumption and emissions for production:

- 95% efficiency of reaction
- energy consumption even in exothermic reactions
- energy and water consumption are average values for chemical plants

- 0.2% of input materials are emitted to air
- water emissions are the difference between the input materials and the air emissions
- no solid wastes

These guidelines were used to estimate data for the following reactions:

- Acetic anhydride and acetone to form acetylacetonone, for both titanium acetylacetonate and aluminum acetylacetonate production.
- Rutile, carbon and chlorine to form titanium chloride.
- Titanium chloride and water to form titanium oxychloride.
- Titanium oxychloride, acetylacetonone and sodium carbonate to form titanium acetylacetonate.
- Aluminum sulphate and acetylacetonone to form aluminum acetylacetonate.

Experimentation gives a rough estimate of 0.12 kg of coating to completely cover 1 m² of surface. Because the surface is coated five times [16], one needs a total of 0.6 kg of coating. The mass ratios of the main chemicals used in this coating were given: boehmite, aluminum acetylacetonate, and titanium acetylacetonate to ethanol as 0.0024, 0.024 and 0.0002, respectively [16]. Balanced chemical equations, molar masses and the given mass ratios were used to calculate the masses of each of these chemicals, as well as the chemicals which make up aluminum acetylacetonate and titanium acetylacetonate. The reactants of equations for which no LCI data were available were multiplied by 1.05263 (1/95%) to account for the assumption of 95% efficiency. The total masses are shown in Table 1.

LCI databases provided production information that included: energy consumption, water consumption, greenhouse gases, and air, water and soil emissions. Energy consumed was determined by summing the energy content of inputs such as coal, natural gas and oil.

LCI data for rutile, chlorine, carbon, acetone, acetic anhydride, sodium carbonate, aluminum sulphate and boehmite came from the Ecoinvent database [28]. Inventory data for the production of corn ethanol were gathered from scientific journals [29,30]. The comparatively large amount of required ethanol makes it one of the major contributors to the coating's environmental burdens. Though omitted for brevity's sake, the same process determined the water repellent's chemical constituents and burdens.

With the mass of each chemical calculated, the appropriate energy consumption, water consumption, greenhouse gasses and

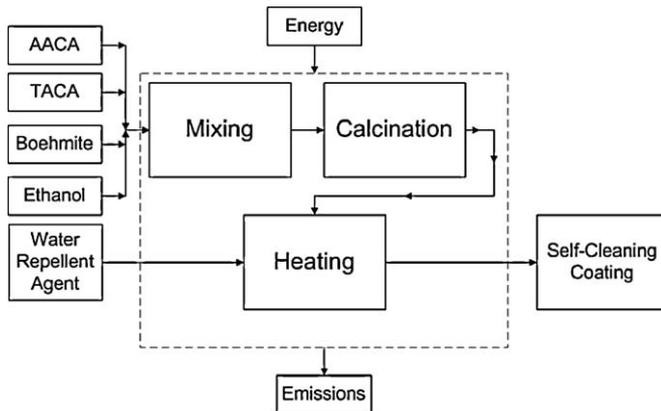
Table 1
Masses of chemicals used in 0.6 kg of self-cleaning coating.

Chemical name	Molecular formula	Mass (g)
Titanium acetylacetonate	TiO(C ₅ H ₇ O ₂) ₂	0.11252
Titanium oxychloride	TiOCl ₂	0.060933
Titanium chloride	TiCl ₄	0.090272
Rutile	TiO ₂	0.039995
Chlorine	Cl ₂	0.071007
Carbon	C	0.012023
Water	H ₂ O	0.008572
Acetylacetonone	C ₅ H ₈ O ₂	0.090546
Acetone	CH ₃ COCH ₃	0.055295
Acetic anhydride	C ₄ H ₆ O ₃	0.097175
Sodium carbonate	Na ₂ CO ₃	0.047915
Aluminum acetylacetonate	Al(C ₅ H ₇ O ₂) ₃	13.5604
Aluminum sulphate	Al ₂ (SO ₄) ₃ *17H ₂ O	14.27683
Acetylacetonone	C ₅ H ₈ O ₂	13.22512
Acetone	CH ₃ COCH ₃	8.0763
Acetic anhydride	C ₄ H ₆ O ₃	14.19336
Boehmite	AlOOH	1.35604
Ethanol	C ₂ H ₅ OH	564.92

Table 2

Inventory data for production of chemicals.

Production of 0.6 kg of self-cleaning coating		
Energy consumed	15.6	MJ
Water consumed	0.525	m ³
CO ₂ emitted	0.576	kg
CH ₄ emitted	3.47E-4	kg
N ₂ O emitted	0.189	kg
Total air releases	0.075	kg
Total water releases	0.120	kg
Total soil releases	1.51E-4	kg

**Fig. 4.** Application of self-cleaning coating to surface.

air, water and soil emissions are determined. The compiled life cycle inventory data for 0.60 kg total coating material and water repellent are shown in Table 2.

3.2.2. Manufacture of coating

The production of the self-cleaning surface involves taking the chemical listed above, mixing them, applying them to a surface, and heating. A flow diagram for the production process is shown in Fig. 4.

The resource consumption of mixing is assumed to be low and therefore not included. Calcination is “heating of a solid to a temperature below its melting point to bring about a state of thermal decomposition or a phase transition other than melting” [23]. Once the coating is mixed, it is applied to a surface and calcinated at 500 °C.

Ethanol accounts for ~90% of the coating mixture’s mass. As a first approximation, one can estimate the energy needed for calcination as the amount of energy required to vaporize this mass of ethanol. A well insulated calcination chamber with minimal convective and radiative heat loss is assumed. Starting the mass of ethanol at standard temperature and pressure ($T_1 = 25$ °C, $P_1 = 101$ kPa, $h_1 = 108.4$ kJ/kg), Eq. (4b), a simplification of the first law in (4a), models the calcination as an isobaric heat addition process that terminates when all of the ethanol is a saturated vapor ($T_{\text{sat}} = 351.3$ K, $h_{\text{sat,v}} = 1108$ kJ/kg).

$$Q_{\text{calcin}} - W = m[(h_{\text{sat,v}} - h_1) + 0.5\Delta v^2 + g\Delta z] \quad (4a)$$

$$Q_{\text{calcin}} = m(h_{\text{sat,v}} - h_1) \quad (4b)$$

This model yields a calcinations heat input, Q_{calcin} , of 565 kJ. At this point, it is assumed that the vaporized ethanol is vented and heat addition continues until the remaining ~65 g of mixture reaches 500 °C. The addition of this comparatively small amount of energy is ignored in this analysis.

In the next steps of production, a water repellent agent is applied to the surface, and it is again heated, this time to only 140 °C (T_{rep}). The surface to be heated is 1 m²; so, it will be assumed that a 1 m³ volume of air will encompass the part or parts on which the coating is applied, for any geometry. The density of air (ρ) is approximately 1 kg/m³. Therefore, the total mass of air to be heated is 1 kg. Taking the specific heat of air ($c_{p,\text{air}}$) as 1.01 kJ/kg K, one calculates the energy needed to heat the coating.

$$Q_{\text{rep}} = m_{\text{air}}c_{p,\text{air}}(T_{\text{rep}} - T_1) \quad (5)$$

One sums the energy consumed in the two steps to obtain the total energy required for coating manufacture. A total of 681 kJ is consumed in the calcination and repellent application of the self-cleaning coating.

One estimates carbon dioxide emissions from the calcination process based on the amount and type of energy consumed [31].

$$\varepsilon_{\text{CO}_2} = CF_e(P_e + P_c) + CF_g(P_g) + CF_sP_s$$

This equation accounts for electricity, steam and natural gas energy sources. Assuming only electricity use, the equation reduces to:

$$\varepsilon_{\text{CO}_2} = CF_e(P_e) \quad (6)$$

In the previous equation, CF_e is 1.40×10^{-7} tons CO₂ per kJ of electricity (kJe), an average for US electricity generation [31]. One uses similar factors for methane (1.235×10^{-9} kg/kJe) and nitrous oxide (2.81×10^{-9} kg/kJe) emissions. Inventory data for the calcination and heating of the self-cleaning coating are summarized in Table 3.

3.2.3. Cleaning self-cleaning surfaces

Even the vaunted Lotus needs rain. Despite the name, self-cleaning surfaces can become contaminated, and they need cleaning. Therefore, one must account for these cleaning burdens in the life cycle inventory.

Experimentation with artificial self-cleaning surfaces on silicon, aluminum and other materials showed that one can clean these surfaces with water alone [32]. Mist cleaning removed nearly 100% of contaminants. Data obtained during these experiments show that one needs approximately 1.5 L of water per 1 m² to achieve this level of cleanliness. An Advanced Misting Systems pump that operates at 6.9 MPa and a flow rate between 1.9 and 3.8 L/min uses 110 V at 6–12 A [33]. To deliver 1.5 L of mist, such a pump requires 47.6–23.8 s. With power consumption between 660 and 1320 W, this pump consumes 62.8–15.7 kJ of electrical energy to deliver the 1.5 L of water mist needed to clean a 1 m² area. One estimates minimum and maximum emissions using Eq. (6) and the given coefficients for CO₂, CH₄ and N₂O (see Table 4).

The previous analysis assumes that the self-cleaning coating’s macroscopic behavior matches that reported by the cited sources. As such, variations in coating quality, thickness and small scale geometry are not considered. These variations may affect performance, but establishing a relationship between micro/nano structures and multi-drop dynamics falls beyond the scope of this work.

Table 3

Inventory data for application of self-cleaning coating.

Energy consumed	0.681	MJ
CO ₂ emitted	0.0953	kg
CH ₄ emitted	8.41E-7	kg
N ₂ O emitted	1.91E-6	kg

Table 4
Inventory data for mist cleaning of 1 m² of a self-cleaning surface.

	Min.	Max.	
Energy consumed	0.0157	0.062.8	MJ
Water consumed	0.0015	0.0015	m ³
CO ₂ emitted	0.0022	0.0088	kg
CH ₄ emitted	1.94E–8	7.75E–8	kg
N ₂ O emitted	4.42E–8	1.76E–7	kg

3.3. Conventional spray cleaning

Cleaning time in a cabinet spray machine ranges from 1 to 10 min [34]. Energy consumption and other specifications were determined from spray cleaning machine industry websites [35]. The spray cleaning machine requires that 2/3 of the tank capacity be reserved for solution.

For 150 L volume part, with 300 L of solution, a total volume of 450 L is needed. The closest available spray cleaning machine has a capacity of 600 L. This machine consumes 25.4 kW. Therefore, the machine's energy consumption for this scenario varies between 1.52 MJ for 1 min and 15.24 MJ for 10. Using Eq. (7), carbon dioxide emissions vary between 0.2128 and 2.128 kg CO₂, and one may determine emission ranges for methane and nitrous oxide in a similar fashion.

For the smaller volume of 12 L, 24 L of solution will be needed, for a total of 36 L. However, the smallest capacity spray machine has a total tank volume of 200 L. This machine uses 6.75 kW; so, the total energy consumption varies from 405 to 4050 kJ with concomitant carbon emissions between 0.0567 and 0.567 kg CO₂.

Typical concentrations of solvent for spray cleaning range from 4 to 30 g/L [36]. The amount of solvent used to clean the 150 L part therefore ranges from 1.2 to 9 kg. To clean the 12 L part, one needs 0.48–0.72 kg of solvent.

A commonly used solvent in the metal cleaning industry is trichloroethylene [37]. The life cycle inventory data of trichloroethylene (TCE) was gathered from SimaPro [28] and is shown in Table 5.

Summing the energy consumption, emissions and water use of the industrial cleaning machines with the inventory data for the solvent completes the life cycle inventories.

4. Results

Table 6 contains the results of the inventories for the self-cleaning coating and four conventional cleaning scenarios. Reading the table from left to right, the first two columns contain data for production and mist cleaning of the bio-inspired coating, respectively. One obtains the entire life cycle impact for one cleaning of a bio-inspired surface by summing the burdens in the first two columns. The middle columns contain data for conventional cleaning scenarios that represent an average of the best and worst case scenarios for conventional spray cleaning in 12 and

Table 6
Life cycle environmental burdens for a single cleaning of a 1 m² self-cleaning surface and untreated surfaces cleaned using conventional spray cleaning.

	Bio-inspired		Conventional spray cleaning scenarios				
	Chemical coating production	Best mist cleaning	Avg. 12 L spray	Avg. 150 L spray	Best 12 L spray	Best 150 L spray	
Energy consumed	16.28	0.0157	4.63	37.01	0.64	4.41	MJ
Water consumed	0.525	0.0015	0.0653	0.812	0.002	0.024	m ³
CO ₂ emitted	0.671	0.0022	4.63	19.138	0.075	0.445	kg
CH ₄ emitted	3.48E–4	1.94E–8	0.0654	1.28E–2	1.37E–5	1.82E–4	kg
N ₂ O emitted	0.189	4.42E–8	1.12E–7	8.21E–5	1.20E–6	5.04E–6	kg
Total air releases	0.075	NA	0.0422	0.522	0.001	0.007	kg
Total water releases	0.12	NA	0.279	3.454	0.004	0.044	kg
Total soil releases	1.51E–4	NA	2.96E–6	3.66E–5	3.76E–8	4.71E–7	kg

Table 5
Inventory data for production of 1 kg of trichloroethylene.

Production of 1 kg of trichloroethylene		
Energy consumed	40.2545	MJ
Water consumed	0.085787	m ³
CO ₂ emitted	0.02065	kg
CH ₄ emitted	0.000175	kg
N ₂ O emitted	0	kg
Total air releases	0.0936	kg
Total water releases	0.61933	kg
Total soil releases	6.56E–6	kg

150 L machines. The last two list conventional cleaning burdens under optimal circumstances:

- Minimum cleaning time (1 min)
- Indefinite solvent recycling
- 5% solvent loss per cycle

To understand the results in terms of durability, one can present Table 6's data as the environmental burden per cleaning of a self-cleaning surface. Consider energy. For 1 m² of surface, Eq. (7) equates the life cycle energy per cleaning (e_{sc}) to the sum of energy used for mist cleaning ($e_{mist} = 15.7$ kJ) and the energy required to make the coating ($e_{coat} = 16.28$ MJ) divided by the number of feasible cleanings (n).

$$e_{sc} = e_{mist} + \frac{e_{coat}}{n} \quad (7)$$

Fig. 5 plots Eq. (7) for a range of feasible cleanings. It identifies the points at which energy consumed per cleaning of a self-cleaning surface equals that of the average and best 12 L spray cleaners.

5. Comparing self-cleaning surfaces and conventional cleaning

Self-cleaning surfaces created using the analyzed coating fail to demonstrate clear environmental superiority. The life cycle

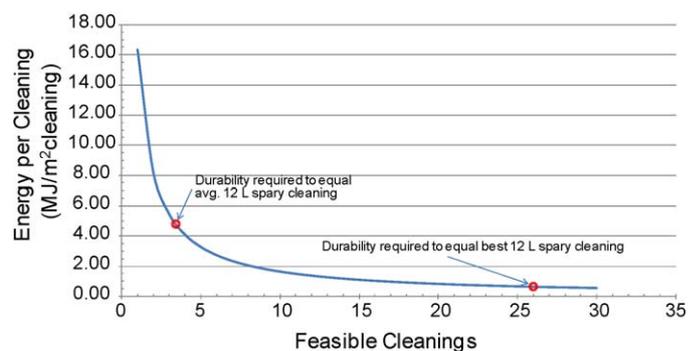


Fig. 5. Life cycle energy required per cleaning of a self-cleaning surface as a function of durability.

inventory summarized in Table 6 reveals comparatively large environmental burdens for self-cleaning surfaces. Some conventional cleaning scenarios dominate self-cleaning surfaces for the tabulated environmental burden dimensions. However, as Fig. 5 illustrates, coating durability can influence this result.

Despite low use phase burdens, the analyzed surface exhibits high total environmental burdens when one considers the entire life cycle. Water mist washing keeps use phase burdens low for self-cleaning surfaces, as shown by the second column in Table 6. The energy consumed to clean the biomimetic surface (15.7–62.8 kJ) falls far below that needed for even the best conventional techniques (640–4410 kJ). But, the burdens of producing the chemical coating drastically increase its burden on the environment. For instance, the self-cleaning surface's 16+ MJ energy consumption estimate is the highest among the five scenarios. Production of constituent chemicals accounts for the majority of these burdens. Of these constituent chemicals, ethanol from corn proved especially burdensome.

When comparing the self-cleaning surface's burdens with those of conventional spray cleaning, one learns that conventional approaches can prove environmentally superior. Short wash times, low solvent loss and high chemical recycling allow even the 150 L washer to dominate the self-cleaning surface. However, under average conditions, the situation becomes far from clear. Self-cleaning surfaces dominate large washers and produce lower burdens than the 12 L washer for some dimensions.

Self-cleaning coating durability holds the potential to change these results. The data in Table 6 assume that the bio-inspired surface only provides self-cleaning benefits for one cleaning. A coating durable enough to survive multiple cleanings distributes the high environmental burdens of production over the number of cleanings. For example, Fig. 5 shows that a coated surface that maintains self-cleaning properties for at least four washes matches the average 12 L washer's per cleaning energy consumption. Durability equivalent to 26 mist washings brings a coated surface to energy parity with the 12 L machine under the best case conditions.

6. Summary and closure

Overall, the LCI study's outcome suggests the need for caution and deliberation on the part of those seeking sustainable engineering guidance from nature and those too quick to dismiss nature's lessons. On the one hand, imitating a feature of many living surfaces did not generate a clear environmental advantage when viewed from a life cycle perspective. On the other, a new technology demonstrated a degree of environmental competitiveness with a mature one. This latter point suggests that investigation of alternate self-cleaning surface production techniques and cleaning scenarios might prove fruitful. The simplifying assumptions used in this first environmental assessment of self-cleaning surfaces represent a separate reason for caution when drawing conclusions from the presented results.

The article presents only one method of creating self-cleaning surfaces; some of the others mentioned in Section 2.3 may prove less environmentally burdensome. Consider laser ablation. Laser ablation creates templates used to imprint small scale surface structures on hydrophobic material [19]. The production phases of a 1 m² template's life cycle consume 890 MJ, but one can create many 1 m² imprints with a single template [38]. Each template may prove durable enough to withstand multiple cleanings. The multiplicative effect of creating multiple durable imprints might distribute the burdens of template creation to the point that it falls below that of even the best conventional cleaning scenario.

The inventory also assumes cleaning parity. In other words, surfaces subject to the same conditions require similar amounts of

cleaning. However, self-cleaning surfaces may prove more resistant to soiling, giving them a comparative advantage over surfaces cleaned in the standard way.

Multiple simplifying assumptions were required to complete this first-order assessment. Assumptions regarding reaction completeness and efficiency, coating application thermodynamics, coating quality and droplet-coating interactions influence the presented results. The possibility that reality may differ with the assumptions documented in the previous sections prevents this assessment from being entirely conclusive. The presence of these assumptions also represents an opportunity to explore the potential impacts variations in reaction chemistries, coating application processes and surface geometry might have on the overall environmental profile of self-cleaning surfaces.

Finally, one should note that the self-cleaning surface's very human methods of creation most contributed to its environmental footprint. One interpretation of such an outcome is that engineering's use of bio-inspiration lacks depth. If one's goal is sustainable engineering, it might prove more fruitful to abstract overarching principles from the living world instead of copying a few features of a specific organism [39].

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