Detergent Performance

Debora Miranda Cortez, Martin Ter Bekke, Zhiwu Liang and Rainer Stamminger*

The impact of detergent performance on sustainable consumer laundry behavior: a socio-technical challenge

https://doi.org/10.1515/tsd-2023-2575
Received December 14, 2023; accepted February 13, 2024;
published online March 8, 2024

Abstract: The laundry process is energy-intensive and an important target for reducing residential environmental impacts. Category life-cycle analysis (LCA) studies show the primary environmental impact is due to the energy consumed during the use phase, mainly for heating water. However, doing the laundry is a complex socio-technical system, where addressing sustainability requires not only technical levers but also an understanding of users' habits, practices, and belief systems. This study investigates if and how consumers change their laundry habits and product satisfaction when using a technically lower-performing eco-brand detergent compared to a heavy duty high-performance detergent. These represent two distinct sustainable innovation strategies within the detergent industry, i) high-performance detergents formulated to provide excellent cleaning performance at lower wash temperatures and ii) eco-brand detergents optimized for a lower ingredient footprint but reducing cleaning performance. It is hypothesized that consumers may compensate in ways detrimental to the overall sustainability of the laundry lifecycle. The results showed significantly lower consumer satisfaction with the eco-brand performance which led to compensatory behavior including increased detergent dosing and higher wash temperatures. This study confirms the importance of detergent cleaning performance for sustainable consumer habit changes regarding lower wash temperatures.

***Corresponding author: Rainer Stamminger**, Universität Bonn ILT, Universität Bonn ILT, Nussallee 5, 53115 Bonn, Germany,
E-mail: stamminger@uni-bonn.de. https://orcid.org/0000-0001-7001-4879
Debora Miranda Cortez, Martin Ter Bekke and Zhiwu Liang, Procter and Gamble Europe SA, Fabric Care Europe Sustainability Product Research, Geneva, Switzerland, E-mail: cortezmiranda.d@pg.com (D.M. Cortez), terbekke.m@pg.com (M.T. Bekke), liang.zw@pg.com (Z. Liang). https://orcid.org/0009-0007-0679-0460 (D.M. Cortez). https://orcid.org/0009-0009-6982-1070 (M.T. Bekke). https://orcid.org/0009-0002-9575-5416 (Z. Liang)

Keywords: socio-technical transition; intervention study; liquid-tablet detergent; France; sustainability

1 Introduction

The continuing rise of greenhouse gas (GHG) emissions is leading to impactful damage in many parts of the world over the coming decades unless GHG emissions can be controlled quickly [1–3]. The objective of reducing GHG emissions can only be achieved if all the sectors that contribute to GHG emissions act responsibly. Clothes-washing consumes an estimated 24.2 TWh/year of electricity and 1.5 km^3 of water in the EU, making it an important target for environmental improvement in the residential sector [4]. In an early phase Stalmans et al. showed in a life-cycle inventory (LCI) that each laundry system has an impact on the environment via the consumption of a broad variety of resources such as crude oil, natural gas, agricultural products and minerals for material feedstock, energy generation and transport purposes [5].

Category LCAs demonstrate that for most indicators of laundry life-cycle analysis (LCA) in Europe the outcome is dominated by the at-home use stage. This is driven by the energy consumption by the washing machine to heat the wash water [6]. The contribution of the use phase to climate change impact is approximately 60 % on EU average, the ingredients account for approximately 20 % [7, 8]. With 80 % of the energy consumption of a washing machine used to heat the wash water [9–11], reducing the wash temperature will provide both sustainability benefits and a financial incentive for consumers.

Over the years, manufacturers of washing machines have substantially reduced water and energy usage by at least 50 % [12–14]. Detergent manufacturers also have made significant progress in reducing their environmental impact with the introduction of enzymes which have allowed for lower wash temperatures and simultaneously improved cleaning performance [15]. Additionally, the move to compact detergent forms provided significant benefits for a range of environmental factors [7].

Another development to influence laundry sustainability is through "eco-brand" detergents that designed according to third party criteria and as a “green signal” to consumers [16]. The most important European eco-certification, the EU Ecolabel, restricts the type of ingredients and their concentration based on a hazard-based approach, which may lead to lower cleaning performance [17, 18].

Research shows that (75–80) % of consumers are not willing to compromise on cleaning performance for perceived sustainability. Consumers are often skeptical about “eco-labelled” products and believe they require a trade-off in performance [19–21]. Since the primary laundry objective is to clean clothes it is hypothesized that lower-performing detergents may cause consumers to engage in compensatory behaviors i.e. higher wash temperature, smaller loads, increased detergent dosing, that would increase the environmental footprint of the full laundry lifecycle [22, 23].

Paloviita and Järvi [24] showed that in the consumption of laundry detergents, consumers do not perceive environmental issues as specific value criteria. They argue that manufacturers and other actors in the value chain of laundry detergents should contribute to alleviating the harmful environmental impacts of the use phase by more effective consumer education and better product design. For consumers, it might be beneficial to adopt eco-efficiency thinking in their daily consumption.

It is estimated that optimizing consumer behavior could save up to 50 % in energy and water consumption [4]. A variety of education and communication strategies have been employed over recent years to convince consumers to adopt more sustainable practices. Many laundry products and marketing campaigns today are designed to promote and enable cold-water washing [25–27]. While these efforts have made some progress in reducing wash temperatures from an average EU wash temperature of 48 °C in 1997 to 41 °C in 2011, A.I.S.E (International Association for Soaps, Detergents, and Maintenance Products) surveys have shown this progress is slowing or plateauing with average temperature back up to 42.4 °C in 2020 indicating the need for new research into the barriers to adopting cold-water washing [26].

Effective efforts to further improve laundry sustainability will require more research into the interactions between technology, consumers, marketers, and regulators. This paper investigates the impact of detergent performance on sustainable laundry behavior by a blinded intervention study.

2 Theoretical background

2.1 Socio-technology interplay and laundry sustainability

Socio-technical systems involve an interplay between a variety of factors and participants including manufacturers, technology, regulators, consumer practices, cultural norms, and infrastructure [28]. Shove [29] presents the case that laundry, while seemingly a routine household task, has all the ingredients of a true socio-technical system (Figure 1). Change in socio-technical systems is difficult because of the need to change not only technology but also the behavior of all the stakeholders in tandem [30]. Transitions in socio-technical systems are often characterized as co-evolutionary because of feedback loops between the different subsystems which modify outcomes and direction [31]. For example, Shove [29] describes the modern washing machine program design as a result of an interplay between clothing fashion designers, synthetic fabrics, environmental concerns, cleanliness standards of excellence, and technology limitations.

Figure 1: Socio-technical system for laundry. Adapted from [32].

2.2 Laundry performance technology factors

The functional objective of clothes-washing is to remove stains and odors so that clothes look and smell clean [22]. Consumers typically judge this by visually examining clothing for stains and brightness, wrinkles, residues, and presence of a fresh, clean scent [33]. The Sinner cycle, first described by Herbert Sinner in 1959, outlines the four independent factors affecting cleaning performance: chemical action, temperature, mechanical action, and time [34]. Lambert et al. [35] and Lasic et al. [36] examined the influence of detergents, washing temperature, washing time, and load on the washing performance in a systematic way. The results clearly showed an increase in washing performance values by increasing detergency, increasing nominal washing temperature, increasing washing time, and decreasing load sizes. Importantly, these levers are not equal in resource use efficiency creating the opportunity for innovation that maintains washing performance while at the same time reducing environmental impact [37]. Indeed, washing machine eco-program cycles take advantage of this by trading off energy intensive hot water for lower temperatures but longer agitation times [38].

Detergents are frequently in the sights of regulators for lowering environmental impact due to their inherent chemical nature [23, 39]. Modern laundry detergents are a complex mix of surfactants, enzymes, builders, optical brighteners, foam regulators, bleaching agents and other minor additives [40]. Most recently, the addition of enzyme ingredients, which perform equally well at lower temperatures, has increased the cleaning performance in cold-water washing, obviating the need for higher water temperatures [25]. Laitala and Jensen [41] studied the washing effects of eight laundry detergents for low-temperature washing at 30 °C and 40 °C. The results show that while many detergents performed equally well at both temperatures, others showed statistically worse performance at lower temperatures, thus indicating detergent selection might play a role in consumer success with the adoption of energy saving cold-water washing.

2.3 Laundry sustainability consumer factors

Despite the progress made in improving the sustainability of washing machines and detergents, consumer behavior can and do counteract these benefits [42]. Consumers are in near-complete control of the all-important in-use factors: wash temperature, cycle time, load size, and detergent dosing [22]. Many of these consumer-dependent variables have significant environmental consequences [42]. Rationally, consumer behavior should be directed by factual information provided by key stakeholders, but in reality it is difficult to influence consumer behavior, especially when dealing with routine daily tasks [43]. Throne-Holst, Strandbakken and Stø [44] detailed the barriers to adopting environmental changes and identified cultural norms and economic concerns as being equal to or more important than information availability. In addition, when a task is routine or habitual, consumers typically invest minimal cognitive effort in decision making. While visible stains and strong malodors are clear physical reasons for washing clothes, for many consumers habit is a principal motivator for washing clothes [45].

In addition to its functional benefit, cleanliness is a cultural construct. The decision to wash clothing is motivated by physical needs, habit, emotion, and perceived community censorship making any change in perceived performance emotionally charged [45]. For many consumers, the elimination of malodor and clean, fresh-smelling clothing is an important part of public self-presentation [46]. The absence of malodor and clean scent are significant motivators for washing clothing. In a survey of 2000 US respondents who had purchased and used laundry, cleaning, and air freshening products in the previous six months, Herz et al. [47] found that 76 % of consumers agreed that smell was the signal of a job "well done" when cleaning clothing, which was significantly higher than the signal they obtained from visual inspection. Also, 36.4 % of consumers stated they would rewash clean clothing if it does not smell clean. For others, clean-smelling laundry may elicit feelings of comfort and security [45]. Concerns about clothing scent and public self-presentation are not unfounded, as Kerr, Rosero and Doty [48] found that when posed with a hypothetical person whose clothing was associated with a canonically clean scent, panelists rated the person as more intelligent, attractive, successful, and sociable than someone whose clothing was associated with a scent not consistent with the concept of clean. Thus, following heretofore successful clothes-washing routines provides consumers with peace of mind and anything that raises doubts about cleaning results could make consumers uneasy [49].

2.4 Research questions

This paper investigates the impact of detergent technology on sustainable behavior in the context of a socio-technical system via an interventional study where study participants (henceforth referred to as "subjects") currently using a detergent marketed as "heavy duty detergent" were given either a similar "heavy duty" detergent (HDD) or an "eco-brand" detergent (EBD) designed to meet Ecolabel criteria. The study tracked the differences in subject acceptance, perceptions, and attitudes towards the two detergents as well as examined their clothes-washing procedures for any habit changes resulting from the change in detergent. Based on the literature discussion, the following questions are posted:

(1) Consumer satisfaction
   a. Is there a difference in overall consumer acceptance of the two detergents?
   b. What differences in performance are perceived by the subjects?

(2) Do washing behaviors vary between the two test detergent legs? Specifically,
   a. Detergent dosing
   b. Wash temperature
   c. Usage of additional products besides detergent
(3) Do consumers consciously attribute any behavior changes to the test detergent?

3 Data and methods

3.1 Study design

The study was a longitudinal blinded in-home use and diary study comparing two liquid tablet detergents: one test product comprising a detergent designed to comply with EU Ecolabel certification criteria (EBD – eco brand detergent) and a control product, which was a regular high performance laundry detergent optimized for in-use performance (HDD – heavy duty detergent) with 69 French consumers in each leg. The EU Ecolabel requires a fitness for use of those 'eco-branded' detergents in requesting that they shall have a satisfactory wash performance at the lowest temperature and dosage recommended by the manufacturer for the water hardness in accordance with 'EU Ecolabel protocol for testing laundry detergents' [50]. However, when technically tested against each other, the eco-brand detergent shows lower technical cleaning performance (see Supplementary Material 5).

The study started with a baseline monitoring period with subjects using their own detergent product for 4 weeks to examine established habits (Table 1). At the beginning of the intervention phase, subjects were given either the EBD or HDD in blinded containers (Figure 2) to use and be monitored for 8 weeks (weeks 5–12). After the intervention phase there was a post-test cool down period where subjects returned to their usual product (weeks 13–18). After this cooldown, post-test qualitative interviews were conducted with select subjects. The subjects did not receive information about the importance of washing at lower temperatures from a sustainability point of view.

3.2 Subject recruitment

This research was conducted in France, with primary household purchasers and users of laundry detergent

Table 1: Study phases and timing.

Study phase	Description	Monitoring	Timing
Baseline	Establishing usual subject behavior patterns using the product they usually purchase	– Per load diaries – Comprehensive questionnaire at end of Week 4	Weeks 1–4 (*March 2022*)
Intervention	Subject usage of study provided products – split between control leg (HDD) and test leg (EBD)	– Per load diaries – Comprehensive questionnaire at end of Week 8 and 12 – Qualitative interviews at end of week 11	Weeks 5–12 (*April–May 2022*)
Post-test	Subjects return to usual product	– Qualitative interviews conducted at the end of week 18	Weeks 13–18 (*June–July 2022*)

Figure 2: Product study blinded packaging and labels. Test product (EBD – coded "FDL" for distribution to subjects) and control product (HDD – coded "MBH" for distribution to subjects), both packed into same pack.

(henceforth referred to as "detergent users") chosen from different parts of the country. The subjects were recruited in February 2022 from a panel owned by a professional agency (La Maison du Test) through the internet. The subjects received monetary incentives for their participation. The following recruitment criteria were applied:

- All subjects needed to be current users of leading detergent liquid tablet product from a brand marketed as high-performance. This was to ensure study subjects were familiar with the liquid tablet form and a high level of performance.
- Detergent users who used laundry additives in more than 25 % of loads were eliminated from consideration to prevent additive use from masking detergent performance. Laundry additives encompass anything placed in the washing machine in addition to detergent – i.e. softener, perfume beads, stain removers, pretreatment products, etc.
- Subjects were required to have a dynamic washing temperature habit, meaning already using more than one wash temperature. The majority (73 %) of potential subjects in the recruiting panel met this criterion.

3.3 Monitoring/data collection

3.3.1 Load diaries

Subjects were given a diary to fill in after every wash load they did at home. This was a short online survey to understand the conditions of the load; clothes/fabric included, fill level, level of soil, temperature & cycle chosen, use of additives, as well as satisfaction on performance (see Supplementary Material 1).

3.3.2 Comprehensive surveys

Subjects were sent a more comprehensive questionnaire on their experience at weeks 4, 8 and 12 (Table 1). The comprehensive questionnaires were aimed at providing an overall summary versus a per-load-only view as collected via the load diaries. This also allowed subjects to share open-ended feedback. All questionnaires were translated into the local language (see Supplementary Material 2–4).

3.3.3 Qualitative interviews

To better understand how the subjects experienced the usage of the study products, 1 h qualitative interviews were done with selected subjects during and after the intervention phase of the study. Based on their diary and questionnaire responses from the intervention mid-point survey (at end of Week 8), 10 subjects were selected who showed noteworthy changes in satisfaction, washing temperature, dosing, or rewashing versus their baseline. These 1 h conversations covered their usual laundry habits as well as their experience with the study products. These interviews were conducted virtually online during the week of May 16th, 2022. As these subjects remained in the study, interviewers did not communicate the aim of the study in order not to bias their behavior but only enquired about their habits and experience.

Qualitative interviews were also conducted with eight subjects after the post-test to gauge how subjects experienced the complete study – including study products usage as well as the return to a product of their choice. As these interviews happened at the very end of the study, in addition to usual laundry habits and experience with the study products, the interviewers also asked these subjects about conscious/unconscious behaviors they displayed. These interviews were conducted virtually online during the week of July 25th, 2022.

3.4 Laundry products used during the study

Both products used in the study were characterized in a laboratory test for cleaning performance using the principles from EU Ecolabel Protocol for testing Laundry Detergents [18]. Stain removal was tested on the standard AISE stain set, over a 30 °C cotton short cycle, as per standard methodology [52]. The control (HDD) product cleaned significantly better in 12 of 14 stains versus test (EBD) product. Whiteness was analyzed based on D-65 W Ganz measurement, with the swatches washed in the control (HDD) product being significantly whiter versus the test (EBD) product (+16.7 points after four washes on cotton, +18 points after four washes on cotton/polyester – a delta of five points is consumer noticeable). Freshness intensity was measured on wet & dry fabrics using an ASTM standard quantitative descriptive analysis with trained sensory panelists [53]. The control (HDD) product was fresher smelling versus the test (EBD) product (+7.5 points on smell of wet fabric and +25.6 points on smell of dry fabric). See Supplementary Material 5 for a full technical characterization of the two products.

The test (EBD) products were sourced from the market and the control (HDD) product directly from the manufacturer's facility. Both products were repacked into identical white tubs for blind unbranded placement (Figure 2), with generic labels including standard dosing instructions, required safety information, and a randomly generated product code. The products were distributed by the local recruitment agency to subjects, including a placement letter to explain the process of the study.

3.5 Measures and statistical analysis

3.5.1 Overall and attribute rating survey responses

Satisfaction with the study products was measured on a per load basis as well as in the comprehensive surveys conducted every 4 weeks. These satisfaction questions included overall rating and specific attribute ratings. Overall Attribute Rating (OAR) is an important measure of user satisfaction. The principal question was: "Considering everything about the test laundry detergent you've been using these past weeks, please indicate the word(s) which best describes your (overall) opinion of this detergent?" Specific attributes, including cleaning, whiteness, scent experience, were also evaluated. OAR and specific attribute answers were asked using a 5-point Likert scale (poor, fair, good, very good, excellent). See Supplementary Material 1–4 for questionnaires. The below section consists of the most relevant and significant results from the questionnaires and diaries.

The comprehensive surveys conducted at weeks 4, 8 and 12 also included additional questions aimed at understanding subject attitudes towards the tested products. One of these questions concerned the intention to purchase this product when it is offered in the market. This was also done on a 5-point Likert scale (I definitely would buy it, I probably would buy it, I might or might not buy it, I probably would not buy it, I definitely would not buy it). Direct questions exploring subject feelings including trust, pride and confidence were also asked using 5-point Likert agree/disagree scale (strongly disagree, disagree, neither agree nor disagree, agree, strongly agree).

For ease of comparison during reporting, the Likert scales were translated into numerical values from 0 to 100 from which a mean can be calculated.

Because Likert scales are not true interval variables, for significance testing, the nonparametric method, Wilcoxon/Kruskal–Wallis test (rank sums) in JMP16.1 (100 SAS Campus Drive, Cary, NC 27513-2414, USA) was used.

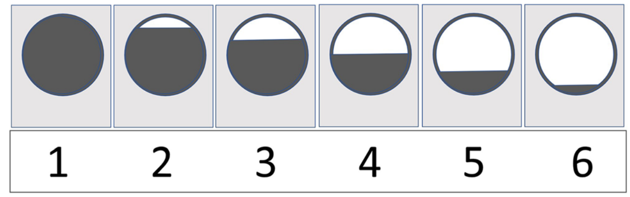

Figure 3: Fill level illustration from load diary.

3.5.2 Wash behaviors

For each load, subjects reported in an online diary regarding the conditions of the wash load. This data was analyzed for the base line period and then over the 8 weeks of study product usage to examine potential changes in laundry habits arising from the study products and to look for potential underlying confounding factors.

- Fill level – Subjects were asked to estimate the fill level of their washing machine on a scale from 1–6 (Figure 3). For analysis, the levels were aggregated into two categories: full (1, 2, 3) and not full (4, 5, 6).
- Soil load – Subjects were asked to input the soil level of their load. For analysis these were aggregated into either "no/little soil" or "moderately to heavily soiled".
- Cycle duration – Subjects were asked to input the duration of their cycle. For analysis, the durations were then aggregated into two groups – under 75 min (considered a shorter cycle) and over 75 min (considered a longer cycle).
- Use of additives (stain removers, softeners, perfume beads) – Subjects were asked to input all the products used in their loads beside detergent by selecting from a list of potential additives.
- Wash temperature – Subjects were asked to fill in the temperature of the wash chosen for the load (based on the temperature indicated on the machine dial).
- Detergent dosing – Subjects recorded the number of laundry pods used for each load.

The percent of washes for each parameter per subject were compared between the control (HDD) leg and test (EBD) leg in absolute values through mixed model. Since each individual subject did many washes during the baseline period (4 weeks) and intervention period (8 weeks), all loads and weekly data are auto-correlated, it is appropriate to apply a repeat measure model for behavioral data. Test product, study week, study week order, and two-way interaction of these factors were treated as fixed effects, baseline average as covariate variable, and participant and study week as repeat effects. The primary outcome was least squares mean for each test product. Student's t was applied as post hoc analysis for products pairwise comparison in different weeks. The Mixed ANOVA model in JMP 16.1 (100 SAS Campus Drive, Cary, NC 27513-2414, USA) was applied.

4 Results

4.1 Data set

118 subjects completed all 3 phases of the study – 4-week baseline and 8-week intervention, – with 59 in each leg (EBD and HDD). This represented a total of 5300 loads of laundry monitored (1716 during the baseline period with their product of choice and 3584 during the intervention phase). 17 subjects also participated in qualitative interviews, both during and after the end of the study.

4.2 Overall and attribute ratings

The comprehensive surveys at the end of the baseline phase when both legs (EBD and HDD) used their own usual high-performance detergent there was no statistical difference in OAR between legs (Table 2). At the end of the intervention phase the test (EBD) leg showed a statistically significant ($p < 0.05$) decline in OAR both versus their baseline and versus the control (HDD) leg. Figure 4 compares the distribution of responses with significantly more "very good" and "excellent" responses for the control (HDD) leg. Along with the reduction in OAR the test (EBD) leg is rated statistically significantly lower in both cleaning performance i.e. cleaning, stain removal, whiteness and freshness attributes i.e. freshness, odor removal, and scent (Table 2). The freshness a detergent provides is influenced by many factors such as perfume composition, the amount of perfume, the cleaning performance and other formulation parameters such as the surfactant system and deposit aids. Eco-labelled products often differ for these parameters from detergents without an eco-label and may explain why the smell of clean is noticeable lower.

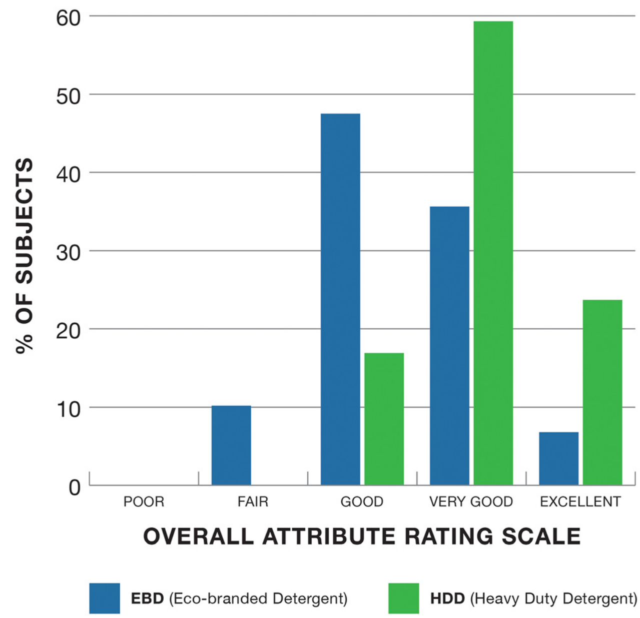

Figure 4: Comparison of distribution of overall ratings (OAR) after 8-week intervention by product leg.

4.3 User attitude responses

In addition to reduced overall rating, the subjects using the test (EBD) product also claimed to be less likely to purchase the product and were less likely to trust the product, feel pride in their laundry and confident in the quality of outcome they expect versus the subjects using the control (HDD) product (Table 3).

Table 2: Comparison of overall and attribute rating means at baseline, midpoint and end of the intervention period.

Study phase	Control high-performance detergent (HDD) (n = 59)	Test eco-brand detergent (EBD) (n = 59)	p
Overall rating (OAR)			
Baseline	60	59	*0.82*
After 4 weeks of product usage	70	49	*<0.001*
After 8 weeks of product usage	73	46	*<0.001*
***Attribute ratings* (*after 8 weeks of product usage*)**			
Cleaning laundry overall	70	49	*0.0002*
Removing spots and stains overall	67	52	*0.0146*
Keeping clothes looking their best over time and new for longer	69	50	*0.0022*
Providing superior/bright whiteness	68	51	*0.0054*
Keeping colors vivid and brigh	71	48	*<0.001*
Scent experience overall	76	43	*<0.001*
Providing long-lasting freshness	76	43	*<0.001*
Removing tough & persistent bad odors	73	46	*<0.001*

Table 3: Comparison of study products mean ratings for purchase intent and emotional factors at week 12 (after 8 weeks of product usage).

	Control high-performance detergent (HDD) (*n* = 59)	Test eco-brand detergent (EBD) (*n* = 59)	*p*
Purchase intent	75	44	*<0.0001*
Direct questions (agree/disagree statements)			
This product is one I feel I can trust and rely on	73	46	*<0.0001*
This product makes me feel proud of my laundry results	71	48	*0.0001*
This product cleans better than others	71	48	*<0.0001*
This product gives me confidence that I will get the results I want, even washing in cold	72	47	*<0.0001*

4.4 Washing behaviors

Six characteristics about individual subject loads were analyzed over the intervention period, comparing them between the control leg and test leg. These differences are reported in Table 4.

In Table 4, two key behaviors showed significant differences ($p < 0.05$) between the control (HDD) and test (EBD) leg on average over the 8-week intervention period: detergent dosing and wash temperature, with the test (EBD) leg subjects increasing detergent use and higher washing temperature. The other parameters did not show a significant difference, meaning that the different performance of the detergents triggers the consumer to adjust mainly the washing temperature and the amount of detergent dosed.

To better understand these compensating behaviors, average wash temperature and dosing were further analyzed over time, looking at data from every load.

4.5 Dosing of detergent

Examination of the data by individual intervention week shows a trend to increasing dosage for the test (EBD) product over the 8-week period without a plateau. The dosage of the control (HDD) product was much more stable after an initial increase at the beginning of the study (Figure 5). The initial increase on both products can be explained by the test conditions, in which the subjects receive free product to test.

If we look at the 8 weeks of testing as 2 periods of 4 weeks (Table 5), the average dosing for the control leg remains stable over the 2 periods of the intervention phase (weeks 5–12). For the test leg, the dosing progressively increases, up to a 0.2 tablet per wash significant ($p < 0.05$) difference between both legs, meaning one more tablet every five washes.

Table 4: Comparison of average washing behaviors during the whole 8 weeks intervention period.

Wash parameter	Least square means		*p*
	Control (HDD)	Test (EBD)	
Wash temperature	36.3 °C	37.2 °C	*0.0221*
Dosing (number of tablets)	1.3	1.4	*<0.001*
Full loads (%)	82	84	*0.1165*
Moderately to heavily soiled (%)	29	29	*0.8213*
Long cycles (%)	30	30	*0.9855*
Loads using additives (%)	11	11	*0.7380*

4.6 Washing temperature

The difference in average washing temperature between control leg and test leg also grows over time, from a 0.6 °C in the first 4-week test period to a 1.1 °C higher temperature for the test (EBD) versus control (HDD) leg in the second period (Table 6).

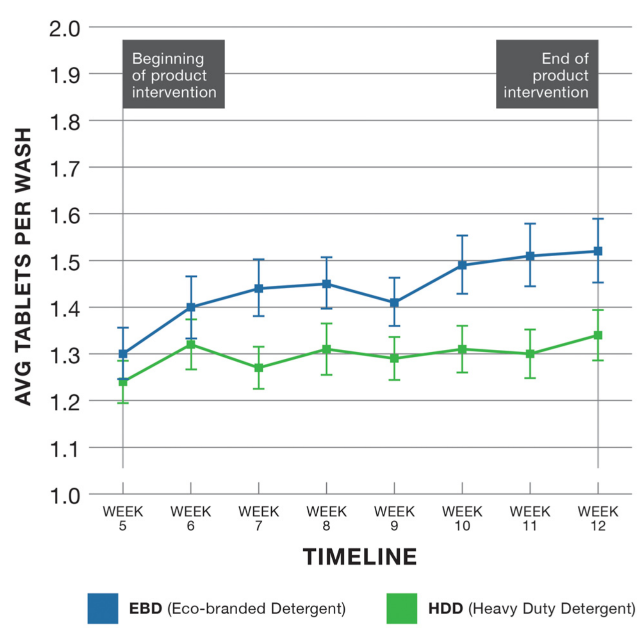

Figure 5: Mean pods dosed per load over time during the intervention phase.

Table 5: Comparison of the average dosing during the two parts of the 8-week intervention period.

Wash parameter	Least square means					
	Weeks 5–8			Weeks 9–12		
	Control (HDD)	Test (EBD)	*p*	Control (HDD)	Test (EBD)	*p*
Average dosing (number of tablets)	1.3	1.4	*0.0203*	1.3	1.5	*<0.001*

Table 6: Comparison of the average wash temperature during the two parts of the 8-week intervention period.

Wash parameter	Least square means					
	Weeks 5–8			Weeks 9–12		
	Control (HDD)	Test (EBD)	*p*	Control (HDD)	Test (EBD)	*p*
Average wash temperature (°C)	36.6	37.2	*0.2231*	36.1	37.2	*0.0474*

Another way to look at washing temperature is to focus on the percentage of loads that are done in cold i.e. 30 °C or below. The percentage of these loads among all loads were analyzed for both legs on both periods of the intervention phase (Table 7). In the first period of the test (weeks 5–8), both legs do similar levels of cold loads. However, in the second part of the test (weeks 9–12), the control leg increases their proportion of cold loads again while the test leg remains at similar level.

4.7 Interview qualitative results

Interviews were conducted with 18 subjects at either week 11 or week 18 of the study for in-depth qualitative understanding. Some example behaviors included subjects doing more/less cold wash versus their habits, starting to use additives, or rewashing. The interviews enabled linking quantitative behavioral data to the subjects' insights and explanations behind them. Some quotes from these interviews are included in the discussion section to illustrate key insights.

5 Discussion

In a socio-technical system such as doing the laundry a change in one part of the process may cause an unintended response from another part of the system [54]. The question to be answered by this study was if in this case consumers notice the change in performance and engage in compensatory behaviors that reduce the potential environmental benefit of EBD.

5.1 Performance differences are noticeable and reduce consumer satisfaction and trust

The first important finding of this study is that the subjects notice the performance difference between HDD and EBD detergents. This is reported via a significant decline for the EBD detergent OAR (Figure 4). This dissatisfaction with EBD performance was seen in ratings for visual cleaning attributes i.e. stain removal and whiteness and was even more pronounced for the "smell of clean" i.e. odor removal and freshness performance attributes (Table 2). The reduced satisfaction led to a significant decrease in purchase intent for the EBD product (Table 3). This is consistent with a study by Shim, Shin and Kwak [55] that found that eco-labeled detergent products which did not deliver equal performance to other detergents resulted in a significant reduction in intent to purchase. Furthermore, test subjects rated the EBD product as less trusted versus the HDD product (Table 3, 46 vs. 73, $p < 0.0001$). Deficient performance over

Table 7: Comparison of percent of loads washed in cold during the two parts of the 8-week intervention period.

Wash parameter	Least square means					
	Weeks 5–8			Weeks 9–12		
	Control (HDD)	Test (EBD)	*p*	Control (HDD)	Test (EBD)	*p*
Percent of cold loads	58.0	55.9	*0.4250*	63.0	57.4	*0.0358*

time may result in loss of trust in labels. Assumptions of having to accept reduced product quality, loss of convenience, or additional expense are a relevant barrier for many consumers to adopt EBD-like products and services [56, 57]. Therefore, poor performance could continue to erode the trust in eco-products as suggested by Shim and Yoshi [55, 57].

5.2 Reduced detergent performance results in consumer compensatory behaviors

The second important finding of this study is that the subjects using EBD products compensate for lower cleaning performance by changing their laundry behavior. The following discusses the two compensatory actions observed: increasing detergent dosing and increasing wash temperature.

5.2.1 Increased detergent dosing is a response to lower detergent performance

Increased detergent dosing was the primary compensatory behavior observed in this study with average dosing being higher for EBD product versus HDD product (Table 4). This is not surprising as detergent dosing is a common tool that consumers vary in response to wash load size, load soil level, and other concerns [58]. In subsequent interviews, subjects in this study who increased their detergent dose commented they did it to compensate for lack of freshness and increasing the dose would provide trust the laundry was sufficiently clean. By dosing two tablets instead of one, they also had more confidence in getting good results no matter what was being washed. These comments underscore the importance of recognizing the priority of clean-looking and smelling laundry in the socio-technical laundry system [22]. One participant started systematically using two tablets of the test detergent during the intervention phase and this is her justification during the interview: “I think I was using two tablets every time. And I’m not doing that with my usual detergent […] I was using two tablets with this one because I was under the impression that the cleaning was not so good […] I believe the reason was to make sure I would get the optimum result.”

Based on the wash results in the first washes people adjust their habits, for EBD products subjects continue to compensate by using significantly more liquid laundry packs in more loads in contrast to the subjects who use HDD that reduce the number of loads with multiple liquid laundry packs.

5.2.2 Increased wash temperature to compensate for lower performance

In this study, the wash temperature for EBD was significantly higher than for the HDD. The 1.5 °C degree difference at the second period of the study (Table 6) is meaningful from an environmental point of view. If everyone in Europe lowered their the wash temperature by 1 °C, it would save 350,000 tons of carbon [25]. Increasing the wash temperature was observed mostly at the second half of the test phase. In post-study interviews, the subjects appeared to make their temperature decisions on “autopilot.” They discussed choosing machine parameters (temperature, time, fill level) more for the definition of the task –for example, cleaning synthetic or delicate fabrics in cold, low agitation cycles or sanitizing underwear and sheets in hot water with long cycles. It is expected that individuals do not reconsider their temperature routine every day, but with enough time and repeated incidents, the trend toward higher temperatures with a lower performing detergent may become a more permanent change. A subject that was doing the majority of loads at 30 °C commented on this during the interview. She used the EBD product and was disappointed with the performance at 30 °C: “it was not really good with my cold wash. […] There were still stains.” She started using more stain remover, which she was unhappy about since it was an additional product – “I’ve tried stain remover just to make sure it would work. It removes the stains, but it’s not the purpose because I don’t want to choose additional products.” – but didn’t change the temperature, explaining it further during the interview: “I have my habits with cold washes and I’m very satisfied with that. I don’t know why I should change the temperature. My detergent should adjust my habits, not the contrary”. However, we can hypothesize that this dissatisfaction over time could lead to an increase in temperature if the product performance in cold wash was not sufficient. In addition, the opposite may also be true, that with repetitive success and education consumer may adopt more frequent cold wash habits. Jackson et al. [43] found that habits in routine tasks require minimal cognitive effort to maintain, making them very difficult to change. This study did not include promotion of cold wash which could have further increased the adoption of lower wash temperatures by the HDD subjects.

6 Future research

6.1 Cold-water washing habit formation and complacency

Given the potential impact of cold-water washing, switching consumers to use more cold-water washes continues to be the holy grail of laundry sustainability [37]. Encouragingly, some geographic regions such as Spain as well as in many other regions outside of Europe already have transitioned to mostly cold-water washes [58]. Research into cultural differences may provide valuable insight into how to overcome the barriers of habit, beliefs, and complacency more broadly.

Even when consumers can see clear differences in performance between detergents, changing washing temperature habit is very slow as also seen in this study and longer test periods should be considered to understand if the habits between EBD and HDD users continue to differentiate further. For many consumers, laundry detergent is a low involvement category, meaning there is low loyalty and frequent brand switching [59]. It may be that the variability in detergent performance from brand to brand does not build consumer confidence in cold-water washing. In this case, it might be useful to research the potential benefit to mandate stringent performance criteria at energy saving cycles also for EBD products, so that consumers are encouraged consistently to build a cold-water wash habit.

Considering the overall lifecycle impact of the laundry socio-technical system, the question needs still to be answered where the absolute acceptable minimum environmental impact is and how it can be achieved. As this intervention study has shown a reduction in performance, due to less and/or lower performing ingredient composition is compensated by consumers by increasing the amount of detergent and using higher wash temperatures, actions that increase the overall environmental impact. This trade-off between detergent performance and compensatory behavior needs to be quantified via LCA to demonstrate lower environmental impacts for the use of heavy duty high performance detergents at lower dose and temperature instead of using lower performing eco-brand products.

7 Conclusions

Residential clothes-washing environmental performance is known in the literature to be the result of a complex interplay of socio-technical factors [26, 29]. This paper adds to this literature by demonstrating the interplay between consumer behavior and laundry detergent cleaning performance. Attempting to improve the environmental footprint of detergents in a manner that results in diminishing cleaning performance has counterproductive effects by causing consumers to engage in compensatory behaviors such as increasing the amount of detergent used or increasing wash temperature. This strategy fails because it discounts the primary motivation for washing: Reducing the cleaning performance for sustainability can be counterproductive as consumers want their primary motivation of clean looking (no stains, whiteness) and smelling (freshness) to be achieved. Instead, detergents with a higher performing ingredient composition that deliver superior cleaning and freshness are more likely to encourage consumers to engage in sustainable washing behaviors that help to reduce the environmental impact of the total wash process.

It is easy to hypothesize that if all manufacturers were forced to make formulation changes that sacrificed detergent cleaning performance, consumers would compensate with extra dosing and higher wash temperatures. Thus, reducing the ingredient footprint of the detergent formulation only of a laundry detergent and sacrificing performance may be counterproductive. LCA data has shown that detergent ingredients themselves play a smaller role in the environmental performance of the laundry process [7]. However, doubling the amount of detergent used per load not only doubles the chemical load, but also the manufacturing, packaging, and shipping costs associated with the detergent's environmental burden.

8 Limitations

Although the study results are consistent with existing consumer knowledge about habits, practices and consumer needs, the geographical scope of this comparative in-home study was limited to France and therefore more studies are needed to demonstrate these findings apply for the general European population.

Research ethics: The research team applied a safety testing policy which provides the basic principles and general guidance for ensuring the rights, safety, and well-being of human testing subjects, in compliance with regulatory requirements and ethical standards derived from the Declaration of Helsinki.

Author contributions: The authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Competing interests: The authors state no conflict of interest. The author Rainer Stamminger is involved in several third party projects funded by different companies producing dishwashers and cleaners.
Research funding: None declared.
Data availability: The data that supports these findings are available upon reasonable request from the corresponding author. Select data may not be available due to privacy or business practices.

References

1. Anderson C. M., DeFries R. S., Litterman R., Matson P. A., Nepstad D. C., Pacala S., Schlesinger W. H., Shaw M. R., Smith P., Weber C., Field C. B. *Science* 2019, *363*, 933–934; https://doi.org/10.1126/science.aaw2741.
2. Morecroft M. D., Duffield S., Harley M., Pearce-Higgins J. W., Stevens N., Watts O., Whitaker J. *Science* 2019, *366*, eaaw9256; https://doi.org/10.1126/science.aaw9256.
3. Obama B. *Science* 2017, *355*, 126–129; https://doi.org/10.1126/science.aam6284.
4. Pakula C., Stamminger R. *Energy Effic.* 2015, *8*, 205–222; https://doi.org/10.1007/s12053-014-9288-0.
5. Stalmans M., Berenbold H., Berna J. L., Cavalli L., Dillarstone A., Franke M., Hirsinger F., Janzen D., Kosswig K., Postlethwaite D., Rappert T., Renta C., Scharer D., Schick K. P., Schul W., Thomas H., Vansloten R. *Tenside Surfactants Deterg.* 1995, *32*, 84; https://doi.org/10.1515/tsd-1995-320205.
6. Faraca G., Spiliotopoulos C., Ranea Palma A., Pérez-Camacho M. N., Alfieri F., Bernad Beltran D., Lag Brotons A., Delre A., Pérez Arriba Z., Arcipowska A., La Placa M. G., Wolf O., Sanye Mengual E., Amadei A., Maury T., Ardente F., Mathieux F. *Ecodesign for Sustainable Products Regulation - Preliminary Study on New Product Priorities (Draft)*; EU Joint Research Centre, 2023; pp. 122–123.
7. Van Hoof G., Schowanek D., Feijtel T. C. J. *Tenside Surfactants Deterg.* 2003, *40*, 266–275; https://doi.org/10.1515/tsd-2003-400507.
8. Golsteijn L., Menkveld R., King H., Schneider C., Schowanek D., Nissen S. *Environ. Sci. Eur.* 2015, *27*, 1–12; https://doi.org/10.1186/s12302-014-0033-2.
9. Sabaliunas D., Pittinger C., Kessel C., Masscheleyn P. *Integr. Environ. Assess. Manage.* 2006, *2*, 142–153; https://doi.org/10.1897/1551-3793(2006)2[142:reuapc]2.0.co;2.
10. Saouter E., van Hoof G. *Int. J. Life Cycle Assess.* 2002, *7*, 103–114; https://doi.org/10.1065/lca2001.09.065.
11. Sabaliunas D., Pittinger C., Kessel C., Masscheleyn P. *Integr. Environ. Assess. Manage. Int. J.* 2006, *2*, 142–153; https://doi.org/10.1002/ieam.5630020206.
12. Ashley S. *Mech. Eng.* 1998, *120*, 94–97; https://doi.org/10.1115/1.1998-mar-6.
13. Bertoldi P., Atanasiu B. *Renewable Energy Status Rep.* 2009, JRC53919; https://doi.org/10.2788/39332.
14. Lebot B., Turiel I., Rosenquist G. Proc. ACEEE 1990 Summer Study Energy Effic. Build. 1990, *1*, 1.147–1.56.
15. Dreja M., Vockenroth I., Plath N., Schneider C., Martinez E. *Tenside Surfactants Deterg.* 2014, *51*, 108–112; https://doi.org/10.3139/113.110289.
16. Iraldo F., Griesshammer R., Kahlenborn W. *Int. J. Life Cycle Assess.* 2020, *25*, 833–839; https://doi.org/10.1007/s11367-020-01741-9.
17. Pastor M. C., Mathieux F., Brissaud D. *Procedia CIRP* 2014, *21*, 415–420; https://doi.org/10.1016/j.procir.2014.03.130.
18. European Union. *EU Ecolabel - Home Laundry Detergents User Manual*, 2022. https://environment.ec.europa.eu/publications/home-laundry-detergents_en (accessed Jan 24, 2024).
19. Luchs M. G., Kumar M. *J. Bus. Ethics* 2017, *140*, 567–584; https://doi.org/10.1007/s10551-015-2695-0.
20. Newman G. E., Gorlin M., Dhar R. *J. Consumer Res.* 2014, *41*, 823–839; https://doi.org/10.1086/677841.
21. Jo M., Shin J. *Int. J. Consumer Stud.* 2017, *41*, 283–290; https://doi.org/10.1111/ijcs.12339.
22. Conrady T., Kruschwitz A., Stamminger R. *Energy Effic.* 2014, *7*, 163–178; https://doi.org/10.1007/s12053-013-9215-9.
23. Minkov N., Lehmann A., Finkbeiner M. *Int. J. Life Cycle Assess.* 2020, *25*, 508–522; https://doi.org/10.1007/s11367-019-01715-6.
24. Paloviita A., Jarvi P. *Int. J. Consumer Stud.* 2008, *32*, 607–612; https://doi.org/10.1111/j.1470-6431.2008.00692.x.
25. A.I.S.E. The case for the AISE low temperature washing initiative substantiation dossier; *A.I.S.E.*: Brussels, 2013. https://www.aise.eu (accessed Jan 24, 2024).
26. Morgan E., Foxon T. J., Tallontire A. *J. Cleaner Prod.* 2018, *190*, 234–250; https://doi.org/10.1016/j.jclepro.2018.04.117.
27. Mylan J. *Organization Environ.* 2017, *30*, 283–303; https://doi.org/10.1177/1086026616677169.
28. Elzen B., Geels F. W., Green K. *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy, 1. General Introduction: System Innovation and Transitions to Sustainability*; Edward Elgar Publishing, 2004.
29. Shove E. System innovation and the transition to sustainability: theory, evidence and policy. In *Chapter 4. Sustainability, System Innovation and the Laundry*; Elzen B., Geels F. W., Green K., Eds. Edward Elgar Publishing, 2004.
30. Chmutina K., Dainty A., Schmidt R. III, Nikolaidou E., Mantesi E., Yu Y., Cook M. *Energy Effic.* 2021, *14*, 92; https://doi.org/10.1007/s12053-021-10003-y.
31. Kemp R., Loorbach D., Rotmans J. *Int. J. Sustainable Dev. World Ecol.* 2007, *14*, 78–91; https://doi.org/10.1080/13504500709469709.
32. Geels F. W. Understanding system innovations: a critical literature review and a conceptual synthesis. In *Chapter 2, System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*; Elzen B., Geels F. W., Green K., Eds. Edward Elgar Publishing, 2004.
33. Stamminger R., Goerdeler G. *SÖFW J.* 2007, *1*, 2–2007.
34. H. Sinner. *Über das Waschen mit Haushaltwaschmaschinen. welchem umfange erleichtern haushaltwaschmaschinen und -geräte das wäschehaben im haushalt?* Haus+Heim Verlag: Hamburg, 1960.
35. Lambert E., Maitra W., Scheid F., Niestrath M., Gorny S., Stamminger R. *Tenside Surfactants Deterg.* 2016, *53*, 424–437; https://doi.org/10.3139/113.110461.
36. Lasic E., Stamminger R., Nitsch C., Kessler A. *Tenside Surfactants Deterg.* 2015, *52*, 193–200; https://doi.org/10.3139/113.110365.
37. Janczak F., Stamminger R., Nickel D., Speckmann H.-D.. *SÖFW-Journal* 2010, *136*, 75.
38. Alborzi F., Schmitz A., Stamminger R. *Energy Effic.* 2017, *10*, 823–838; https://doi.org/10.1007/s12053-016-9486-z.
39. McCoy M. *Trade Group Confronts Emerging Chemical Regulations*; Chemical & Engineering, News, 2006.
40. Gürkök S. *Int. J. Sci. Eng. Res.* 2019, *10*, 75–81.
41. Laitala K., Jensen H. M. *Tenside Surfactants Deterg.* 2010, *47*, 413–420; https://doi.org/10.3139/113.110096.
42. Laitala K., Boks C., Klepp I. G. *Int. J. Consumer Stud.* 2011, *35*, 254–264; https://doi.org/10.1111/j.1470-6431.2010.00968.x.
43. Jackson T. *Sustainable Dev. Res. Netw.* 2005, *29*, 30–40.

44. Throne-Holst H., Strandbakken P., Stø E. *Manage. Environ. Qual. Int. J.* 2008, *19*, 54–66; https://doi.org/10.1108/14777830810840363.
45. T. Jack. *Int. J. Consumer Stud.* 2013, *37*, 666–674; https://doi.org/10.1111/ijcs.12048.
46. Pink S. *Soc. Anthropol.* 2005, *13*, 275–290; https://doi.org/10.1111/j.1469-8676.2005.tb00391.x.
47. Herz R. S., Larsson M., Trujillo R., Casola M. C., Ahmed F. K., Lipe S., Brashear M. E. *Cognit. Res. Princ. Implic.* 2022, *7*, 1–20; https://doi.org/10.1186/s41235-022-00378-6.
48. Kerr K.-L., Rosero S. J., Doty R. L. *Perceptual Motor Skills* 2005, *100*, 135–141; https://doi.org/10.2466/pms.100.1.135-141.
49. Kaufmann J.-C.. *La trame conjugale: analyse du couple par son linge*; Armand Colin, 2014.
50. The European Commission. E. Union. COMMISSION DECISION (EU) 2017/1218 of 23 June 2017 establishing the EU Ecolabel criteria for laundry detergents, in *2017/1218*; European Union, 2017
51. World Medical Association. *Bull W. H. O*. 2001, *79*, 373–374.
52. A.I.S.E. Laundry Detergent Testing Guidelines - Minimum Requirements for Comparative Detergent Testing, 2020. https://www.aise.eu/our-activities/standards-and-industry-guidelines/laundry-detergent-testing-guidelines.aspx (accessed Jan 24, 2024).
53. Bleibaum R. N., Tao K. W. C., Thomas H. Quantitative descriptive analysis. In *Chapter 3, Manual on Descriptive Analysis Testing for Sensory Evaluation*; Bleibaum R. N., Ed. ASTM International: West Conshohocken, PA, 2020.
54. Kemp R., Loorbach D., Rotmans J. *Int. J. Sustainable Dev. World Ecol.* 2007, *14*, 78–91; https://doi.org/10.1080/13504500709469709.
55. Shim D., Shin J., Kwak S. Y. *Bus. Strategy Environ.* 2018, *27*, 1409–1421; https://doi.org/10.1002/bse.2192.
56. Grankvist G., Biel A. *J. Environ. Psychol.* 2001, *21*, 405–410; https://doi.org/10.1006/jevp.2001.0234.
57. Joshi Y., Rahman Z. *Int. Strategic Manage. Rev.* 2015, *3*, 128–143; https://doi.org/10.1016/j.ism.2015.04.001.
58. Alborzi F., Schmitz A., Stamminger R. *Int. J. Consumer Stud.* 2017, *41*, 671–684; https://doi.org/10.1111/ijcs.12380.
59. Mendez M., Bendixen M., Abratt R., Yurova Y., O'Leary B. *Int. J. Educ. Soc. Sci.* 2015, *2*, 103–117.

Supplementary Material: This article contains supplementary material (https://doi.org/10.1515/tsd-2023-2575).

Bionotes

Debora Miranda Cortez
Debora Miranda Cortez is interested in how our daily products can enable us to lower our environmental footprint. After a master's engineering degree at the National Graduate School of Chemistry of Montpellier (FR), she joined Procter & Gamble in Belgium to work on circular packaging & eco-design. She is now focusing on sustainable innovation and consumer understanding. She aims to innovate for products that can delight consumers while still reducing carbon emissions and driving responsible habits.

Martin Ter Bekke
Martin ter Bekke is interested in science-based marketing and communication to promote sustainable habits. He is a P&G employee for 14 years after graduating at Utrecht University (NL) with a MSc. degree in Science and Business Management. In his current position as Scientific Communications Director his focus area is to bring together the internal technical expertise and product propositions and external experts, stakeholder believes and consumers needs to help shape business strategies and brand communication.

Zhiwu Liang
Zhiwu Liang is a Principal Statistician for Fabric Care at P&G in Belgium. He has been working at P&G for 23+ years after he got a PhD from University of Groningen. His focus is design experiment, multivariate analysis, PLS regression model and path model for interaction effect and quadratic effect, growth curve model in SEM, choice model for consumer willing to pay, Word2Vector model for text analytical, and ML model for consumer preference and image analysis.

Rainer Stamminger
Rainer Stamminger, University of Bonn. Rainer Stamminger was appointed Professor of Appliance and Process Engineering at the University of Bonn in 2002. The main areas of research at the University are consumer behavior of household work with and without using appliances, new products or features, smart appliances, robots for household application, and questions of sustainability of housekeeping. He is now Senior-Professor at the University of Bonn and running his own business for consultancy and services.