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Quantitative Assessment of Cost Implications for Sustainability in the Knitwear Industry

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ABSTRACT

Sustainable textile production aims to reduce environmental impact, yet the financial trade-offs remain a critical concern for manufacturers. This study provides a quantitative assessment of the cost implications of implementing sustainability measures in the fabric finishing department of a knitwear industry. Three finishing setups were analyzed – conventional, intermediate, and fully sustainable – focusing on resource consumption (water and chemicals) and production costs for a standard 180 gsm cotton knit polo shirt. Data were collected via detailed industrial surveys on process-wise water use, chemical inputs, and cost breakdowns. The sustainable finishing unit achieved drastic reductions in water usage (~24 L/kg vs. 46 L/kg in conventional processing) and chemical consumption (e.g. eliminating enzyme use and cutting hazardous chemicals by ~30–50%), thereby minimizing environmental footprints. However, these gains came with higher production costs: the sustainable process incurred the highest fabric and garment cost per unit, roughly 2–3× the conventional cost. The intermediate scenario showed moderate improvements in resource efficiency with milder cost increase. Despite greater upfront costs, sustainable practices yielded long-term benefits in compliance, brand value, and product quality, and commanded a premium price that offset some costs. The results underscore that investing in cleaner production technologies and eco-friendly processes can be economically viable when considering lifecycle benefits and evolving market/regulatory pressures. This comprehensive cost-benefit analysis offers critical insights for textile manufacturers and policymakers seeking to balance sustainability goals with economic performance in the pursuit of a more sustainable fashion industry.

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Introduction

The textile and apparel industry is among the most resource-intensive and polluting industrial sectors, driving urgent calls for more sustainable manufacturing practices. From fiber production to fabric finishing, textile processes consume vast quantities of water and energy and discharge pollutants, contributing significantly to global carbon emissions and water scarcity. For instance, traditional wet processing (dyeing and finishing) relies on fresh water and hazardous chemicals, raising concerns about freshwater depletion and water pollution . In fact, manufacturing activities worldwide contribute over 20% of carbon dioxide emissions, and the textile supply chain is a notable part of this footprint. Sustainability in this context refers to meeting present production needs without compromising the ability of future generations to meet theirs, encompassing environmental conservation, economic viability, and social responsibility.

Achieving sustainability requires simultaneously reducing environmental impact, maintaining profitability, and ensuring social compliance – often termed the "triple bottom line" or three pillars of sustainability . In recent years, consumer awareness and regulatory frameworks have intensified pressure on textile manufacturers to adopt eco-friendlier processes. Global initiatives such as the United Nations Sustainable Development Goals (SDGs) and the European Green Deal are pushing the industry toward circular economy principles and stricter environmental standards. Extended Producer Responsibility (EPR) laws, for example, encourage brands to design products for durability, reuse, and recyclability, under threat of losing market access or facing penalties if they fail to adapt. As a result, many firms are exploring sustainable manufacturing innovations – from biodegradable materials to waterless dyeing and closed-loop recycling – not only to reduce their ecological footprint but also to remain competitive under evolving legislation. Indeed, forward-looking companies recognize that implementing sustainable practices can improve operational efficiency, enhance brand reputation, and mitigate regulatory and supply-chain risks in the long run.

Despite the clear environmental benefits and policy drivers, a key barrier to sustainability in textiles is the perceived increase in production costs. Eco-friendly materials and processes (such as organic cotton, low-impact dyes, advanced treatment of effluents, renewable energy usage) often require higher initial investment or incur higher

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unit costs . Traditional cost accounting in the industry typically overlooks the long-term savings and external benefits of sustainable practices, focusing instead on immediate expenditures. This can make sustainability initiatives seem economically unattractive, especially for resource-constrained manufacturers in highly competitive markets. There is a need for rigorous analysis that quantifies both the costs and benefits (tangible and intangible) of sustainable production to inform better decision-making. Previous studies and reviews have highlighted that while initial costs for cleaner technologies can be high, they often yield downstream savings by reducing resource consumption, waste treatment needs, and by opening opportunities for premium pricing. For example, sustainable manufacturing approaches integrate lifecycle assessment and environmental costing to capture expenses related to raw material sourcing, energy use, and waste management, offering a more comprehensive view of true production cost . Early adoption of such practices can also preempt future compliance costs and strengthen a company's market position as sustainability becomes a mainstream consumer expectation . Within textile manufacturing, the fabric finishing stage (including pretreatment, dyeing, and final finishing processes) is particularly critical. It is both resource-intensive and value-adding, and thus a prime target for sustainability improvements. Finishing processes account for a large share of water use and chemical discharges in textile production. Technologies such as enzymatic treatments, low liquor ratio dyeing, and closed-loop rinse water recycling have been introduced to mitigate these impacts. Some innovative mills have reported substantial reductions in water and effluent loads through cleaner production measures.

However, comprehensive financial evaluations of such measures – particularly in a real industrial context – are limited. Manufacturers are keen to know: How do sustainable finishing practices affect the overall cost of producing a garment, and are the environmental benefits achieved at an acceptable cost?

This research addresses that question by conducting a detailed comparative case study in a knitwear fabric finishing context. It builds upon the thesis work by Mah Gul (2025), which gathered first-hand industry data from three knitwear manufacturing setups representing different levels of sustainability adoption. By comparing a conventional finishing department (minimal sustainability measures) with an intermediate department (partial implementation of cleaner processes) and a sustainable department (state-of-the-

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art sustainable practices), we can quantify the cost differences and resource savings attributable to sustainability. The focus is on a single product type (cotton knit shirts) to provide a consistent basis for comparison. The analysis spans both the materials processing stage (knit fabric production including yarn, knitting, dyeing costs) and the garment finishing stage (cut-make-trim and associated costs), alongside metrics for water and chemical consumption in each scenario. By integrating the experimental/field data with insights from literature, the study forms a coherent narrative on sustainable textile production – from motivation and background, through methodology, to results and implications. In the following sections, we first describe the materials and methods, including the industry survey approach and metrics used. We then present and discuss the results, highlighting how conventional vs. intermediate vs. sustainable finishing units differ in cost structure, water usage, and chemical use. We discuss the cost-benefit implications in the context of environmental impact reduction and emerging policy and market trends. Finally, we conclude with recommendations for industry and policymakers, suggesting how sustainable practices can be scaled up and where further research is needed to support a greener and economically viable textile sector.

Materials and Methods

Case Selection: To assess varying levels of sustainability in fabric finishing, three knitwear manufacturing units were selected as case studies, characterized as *conventional*, *intermediate*, and *sustainable*. Each unit produces similar products – specifically, 100% cotton knitted polo shirts of 180 g/m² (GSM) fabric weight – which provides a common basis for comparison. The conventional unit operates with standard practices and little emphasis on sustainability (e.g. using standard cotton, typical chemical recipes, and no special resource-saving technologies). The intermediate unit has implemented certain eco-friendly measures (for instance, partially sustainable raw materials or some process optimizations) but not a full sustainability transformation. The sustainable unit represents a best-practice scenario, claiming fully sustainable production methods (such as using organic or BCI-certified cotton, advanced machinery with water/energy-saving features, and comprehensive waste management). These three cases allow a direct comparison of resource usage and costs under different sustainability paradigms.

Data Collection: A quantitative survey instrument was developed to capture detailed

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process-wise data from each unit . The questionnaire was divided into three main sections corresponding to key resource and cost factors: (1) Water Consumption, (2) Chemical Consumption, and (3) Production Cost Breakdown. Respondents (production managers, process engineers, or relevant staff at each factory) were asked to provide measured or best-estimate values for each metric, based on processing *1 kg of fabric*. This functional unit (per kg of fabric) ensures the data from different factories are normalized and comparable.

- *Water Consumption:* For each major stage of wet processing in fabric finishing, the survey requested the volume of water (in liters) used per kilogram of fabric processed. The stages included De-oiling, Scouring & Bleaching, Neutralizing & Enzyme Treatment, Dyeing, and pH Off-loading (final rinsing). If a particular stage was not used or was combined with another in a given facility (e.g. if de-oiling is skipped due to cleaner yarns, or scouring and bleaching are done in one bath), the respondents would indicate zero or the combined value accordingly. This allowed capturing any process integrations that reduce water usage. The total water consumption per kg for all finishing processes was also recorded .
- *Chemical Consumption:* The survey similarly gathered data on key chemicals used in finishing, recorded as concentration per liter of processing bath (grams per liter, or % in the case of dyestuff) . Specifically, it covered chemicals typical to each wet process stage: e.g. detergent (for de-oiling), hydrogen peroxide (H_2O_2) for scouring, sodium hydroxide (NaOH) for bleaching, acetic acid for neutralization and pH adjustments, enzymatic reagents (like cellulase for bio-polishing), and dye concentration used in the dye bath . These inputs highlight differences in chemical intensity and types between conventional and sustainable approaches – for instance, whether enzymes are used instead of harsh chemicals, or if lower concentrations suffice in optimized processes.
- *Production Cost Breakdown:* To link resource use with economics, the survey collected a breakdown of production costs for the same product across the three units . The cost data were separated into two phases reflecting the manufacturing stages: (i) Fabric Production Costs – including raw material (yarn) cost, knitting cost (including any waste or scrap), and dyeing/finishing cost per kg

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of fabric – and (ii) Garment Making and Finishing Costs – including cut-make-trim (CMT) labor cost, any outsourcing or freight cost, accessory and trim costs (like collars, buttons, labels), overheads, and profit margin. All cost figures were requested in a consistent currency (e.g. USD) per standard quantity (per kg or per piece as applicable). For uniformity, we converted per-piece costs into per-kg costs using the average fabric weight per shirt in each case, enabling direct comparison on a per-kg basis file-fpjutyrdy4sohhodgtfxkh. It should be noted that "profit" here represents the manufacturer's markup or margin per unit, which provides insight into pricing strategies under each scenario.

Production and Process Details: In addition to numerical data, qualitative information about each unit's practices was gathered to contextualize the numbers. This included whether the unit uses different cotton fiber types (e.g. conventional vs. organic cotton), any notable machinery differences (e.g. use of low-liquor-ratio dyeing machines or energy-efficient dryers), and process adjustments (such as combining steps or using alternative chemicals). For example, the sustainable unit reported using high-quality, clean cotton that required no de-oiling step, whereas the conventional unit performs a separate de-oiling wash due to oil residues from knitting . The intermediate unit partially adopted such practices, which might omit or streamline certain steps. Similarly, information on liquor ratios (ratio of water to fabric weight in processes) was collected since this directly influences water and chemical use. The sustainable facility typically operated at lower liquor ratios (e.g. 1:6) in dyeing and rinsing, compared to higher ratios (e.g. 1:10 or more) in a conventional setup . This kind of process-level detail helps explain the quantitative differences observed.

Data Analysis: The collected data were tabulated and compared across the three sustainability levels. We calculated totals (e.g. total water per kg, total cost per kg) and examined the contributions of each sub-component. For cost analysis, two tables were prepared: one for fabric production costs per kg (from yarn to finished fabric) and one for garment finishing costs per kg (from fabric to finished shirt). For water and chemicals, the usage at each process stage was compared to identify which stages contributed most to differences between conventional and sustainable approaches. Because the data come from industry sources (and not a controlled lab experiment), no formal statistical tests were

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applicable; instead, the analysis is a direct empirical comparison. The discussion therefore focuses on the magnitude of differences and their practical implications. To ensure data reliability, the information from each company was cross-checked where possible (for instance, verifying that the sum of water per stage matched the reported total water, or that cost per piece times pieces per kg matched cost per kg). Any anomalies were clarified with the respondents. Overall, the methodology provides a real-world, holistic picture of how implementing sustainable practices in fabric finishing can shift both resource footprints and cost structures.

Results and Discussion

Cost Analysis: Conventional vs. Intermediate vs. Sustainable Units

Fabric Production Costs (Stage 1): Significant cost disparities were observed in the production of finished knit fabric among the three units, driven by differences in raw material choices and process efficiencies. Table 1 summarizes the cost of raw materials and processing to produce 1 kg of dyed knit fabric ready for garment manufacturing in each case. The sustainable unit had the highest material cost, with total yarn cost about $4.05 per kg compared to $3.46 in the conventional unit . This reflects the use of premium sustainably-sourced yarns (e.g. organic or long-staple cotton) in the sustainable facility, which are more expensive due to higher quality and certification costs. The intermediate unit's yarn cost was moderate at $3.71/kg, as it blends standard and some better-grade cotton. Knitting conversion costs also differed: the sustainable unit incurred $0.75/kg for knitting (including wastage), substantially higher than the $0.10/kg in both conventional and intermediate cases . This higher knitting cost may arise from slower production speeds or additional quality control to handle the fine sustainable yarns, as well as potentially higher labor costs if the sustainable unit ensures fair wages . By contrast, the conventional and intermediate units, using standard machinery and methods, knit at lower cost, albeit possibly with more waste or lower precision .

After knitting, the pretreatment and dyeing processes add further costs. The conventional unit showed a dyeing cost of about $1.07/kg , which was the lowest among the three. The sustainable unit's dyeing cost was slightly higher at $1.70/kg , due to the use of eco-friendly dyes (including natural or low-impact synthetic dyes) and the operation of advanced dyeing methods that, while saving water and chemicals, can involve

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higher operating expense or slower throughput . Surprisingly, the intermediate unit reported the highest dyeing charge at $1.78/kg . This could be due to less efficient resource recovery – for instance, the intermediate facility might use moderately priced dyes but without the full optimizations of the sustainable unit, leading to higher consumable usage or external processing costs (such as effluent treatment charges). It might also reflect outsourcing of dyeing or smaller batch sizes. Following dyeing, finishing/washing costs were reported as $0.53/kg for the conventional unit, $0.25/kg for the sustainable unit, and $0 for the intermediate unit . The intermediate unit's zero cost suggests that it integrated the final finishing in the dyeing step (a common practice in more modern setups, where no separate finishing wash is needed or it's accounted for in dyeing cost). The sustainable unit still had a small finishing cost, possibly for specialized finishing treatments (e.g. enzymatic bio-polishing or softeners that are eco-friendly). The conventional unit likely incurred this cost in separate after-washes or softening treatments using conventional methods.

Combining these, the total cost to produce 1 kg of finished fabric was approximately $6.76 for the sustainable unit, versus $5.16 for the conventional unit, with the intermediate at $5.59 . This means the sustainable fabric was about 31% more expensive per kg than conventional fabric at the production stage. Another perspective is cost per garment: given the weight of a polo shirt, the cost of fabric per piece came out to around $2.46 for the sustainable shirt, $1.11 for the conventional, and $1.81 for the intermediate . This indicates the sustainable product used a bit more fabric mass per piece (potentially due to higher material waste in cutting or heavier fabric) and/or higher cost per kg. In summary, at Stage 1, the sustainable approach incurs higher costs due to more expensive yarn and processing – consistent with its focus on quality and environmental compliance – while the conventional approach minimizes cost at the expense of using cheaper inputs and potentially forgoing quality or sustainability. The intermediate strikes a middle ground, with costs only slightly above conventional for yarn and equal knitting cost, but higher in dyeing (perhaps reflecting partial investment in cleaner technology without full efficiency gain). As a result, the intermediate fabric cost is just 8% above conventional, illustrating that moderate sustainability improvements do not necessarily heavily penalize fabric cost.

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Garment Making and Finishing Costs (Stage 2): Beyond fabric production, we evaluated the cost of converting the fabric into a finished garment (the polo shirt) – often termed *Cut-Make-Trim* (CMT) and associated overheads. Table 2 presents the cost components per kg of garments (shirts) for the three units . A clear gradient is seen: the conventional unit has the lowest total at $2.35 per kg of shirts, the intermediate moderate at $3.46/kg, and the sustainable unit significantly higher at $6.61/kg . Several factors contribute to this disparity:

- **Cut-Make-Trim (CMT) Labor:** The sewing and assembly cost was $0.25/kg for conventional, versus $0.41/kg for both intermediate and sustainable . This suggests that the intermediate and sustainable factories invest more in labor (possibly higher skilled or paid labor) or have more labor-intensive quality control, whereas the conventional likely minimizes labor cost (which could risk lower workmanship quality or labor conditions) . Ethical production standards in the sustainable unit likely ensure workers are paid living wages, hence the higher CMT cost .
- **Freight/Outsourcing:** Interestingly, the sustainable unit had $0 freight cost, whereas the conventional and intermediate had a small freight cost (around $0.026–$0.029/kg) . This reflects that the sustainable facility likely performs all processes in-house (vertical integration), eliminating the need to ship materials out for subcontracted work. The other two possibly outsource certain parts of production (e.g. knitting or printing done off-site), incurring transportation costs and associated environmental footprint. The sustainable practice of localization not only cuts cost here but also reduces carbon emissions from transport .
- **Collar and Accessories:** The cost of collars (knitted collar and cuffs) was vastly different – only $0.05/kg in conventional, $0.12 in intermediate, and $0.41 in sustainable . Similarly, accessory/trim costs (buttons, labels, packaging) were $0.37, $0.49, and $0.35 respectively . The higher collar cost in sustainable could indicate the use of expensive sustainable materials or a more complex collar manufacturing process (perhaps ensuring the collar yarns are organic or dyed with low-impact dyes, increasing cost) . The intermediate collar cost is somewhat in between, possibly using partly better materials. Accessory costs did not follow a

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strict monotonic pattern – the intermediate was highest, maybe due to including some special trims, whereas the sustainable kept accessory cost relatively controlled (possibly using simpler or fewer trims to maintain sustainability ethos, or benefitting from economies in bulk sustainable accessories). In all, these differences highlight that sustainable products may incorporate costlier components (like certified accessories), though smart material choices can contain some trim costs.

- **Overheads:** Overhead (which can include utilities, administrative costs, compliance costs, and depreciation of equipment) climbed from $0.27/kg in conventional to $0.43 in intermediate, up to $0.67 in the sustainable unit . A higher overhead in sustainable production is expected because of investments in advanced technology (e.g. water treatment plants, renewable energy installations, environmental certifications) which add to fixed costs . Additionally, maintaining sustainability standards often entails additional management and reporting efforts (e.g. audits for certifications like OEKO-TEX or GOTS), contributing to overhead. The intermediate unit's overhead is midway, perhaps having some improved infrastructure but not to the same extent as the sustainable facility.
- **Profit Margin:** One striking difference is the *profit* component. The sustainable unit includes a much higher profit allocation, about $2.31 per kg of shirts, whereas the intermediate's profit was $0.27 and conventional only $0.17 . In percentage terms, if we consider the "Total" as a proxy for selling price per kg, the sustainable model's profit is about one-third of the total cost (35% margin), while conventional operates on a very thin margin (~7%) and intermediate around 8%. This aligns with the market reality that sustainably produced garments can command a premium price from consumers . The sustainable company likely prices its product significantly higher, banking on its eco-friendly branding to yield higher profit per unit. The conventional manufacturer, by contrast, competes on razor-thin margins in commodity markets . This finding is crucial: it suggests that although sustainable manufacturing incurs higher costs, it may also enable higher revenues per product, partially or fully offsetting those costs. In this case, the sustainable shirt's selling price (reflected by cost+profit) is roughly $6.61/kg +

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margin vs $2.35/kg + small margin for the conventional. The willingness of the market to pay more for sustainable apparel is a key factor in economic viability, and here it appears the sustainable unit leverages a "premium product that commands a higher market price" .

In summary, the total cost per finished shirt (combining Stage 1 and Stage 2 per piece) would be lowest for conventional, moderate for intermediate, and highest for sustainable. Based on the per-kg totals, a single sustainable polo (weighing ~0.3 kg) might cost the producer roughly $ (6.76+6.61)*0.3 ≈ $4.0 (with a selling price including profit perhaps higher), vs. a conventional polo of 0.215 kg costing (5.16+2.35)*0.215 ≈ $1.65. These approximate comparisons illustrate the stark contrast. However, it is critical to view these costs in context – the sustainable model's costs include investments that yield substantial environmental benefits and likely long-term savings, which we explore next, and its pricing strategy recovers much of the added cost from the market. The intermediate model shows that many improvements can be made with relatively small cost increases (fabric +8%, garment +~47% per kg, which on a per-shirt basis is maybe a dollar more than conventional) – a middle path that might appeal to firms starting sustainability transitions.

Water Consumption in Wet Processing

Water is a vital input in fabric finishing, and its usage is a direct indicator of environmental efficiency. The data reveal a dramatic reduction in water consumption as we move from conventional to sustainable processes . Figure 3.3 illustrates water use at each major processing stage for the three scenarios. The conventional finishing process consumed about 46 L of water per kg of fabric in total. In contrast, the intermediate process used roughly 30 L/kg, and the sustainable process only 24 L/kg . These totals encapsulate several process differences:

- **De-oiling:** In the conventional unit, an initial washing step to remove knitting oils used about 7 L/kg of water. The intermediate and sustainable units effectively eliminated the de-oiling stage, using high-grade cotton that is low in residual oils or employing knitting machinery that avoids heavy oil contamination . By omitting this step, they save those 7 L outright. This highlights how selecting better raw materials (cleaner yarn) or pre-cleaning machinery can reduce the need

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for resource-intensive cleaning processes .

- **Scouring & Bleaching:** Traditionally, scouring (removing natural waxes/impurities) and bleaching (whitening) are done in separate baths. The conventional facility followed this, resulting in a cumulative water use of about 14 L/kg for these two steps (often ~7 L each) . The intermediate facility combined scouring and bleaching in one bath, a cleaner production approach that used only 7 L/kg . The sustainable unit went further by operating at a *low liquor ratio* of 1:6 (meaning 6 L of water per 1 kg fabric) for this combined step, thus using just 6 L/kg . This improvement reflects both technological upgrades (equipment that can handle low liquor ratios) and process integration. Achieving a 1:6 ratio from a conventional 1:10 or 1:12 is significant – it indicates water savings of ~40% in this stage alone, without compromising fabric preparation quality.
- **Neutralization & Enzyme treatment:** After bleaching, fabrics are usually neutralized (to remove alkaline residues) and sometimes treated with enzymes (e.g. cellulase for bio-polishing). The conventional process used a liquor ratio around 1:7 here, consuming 7 L/kg . Both intermediate and sustainable units standardized this step at 6 L/kg (liquor 1:6) . The fact that even the intermediate achieved 6 L suggests that modern enzyme processes were adopted there too, indicating a fairly widespread acceptance of optimized recipes. The sustainable unit likely also benefitted from using fewer harsh chemicals (as we will discuss later), making rinse processes easier and requiring less water.
- **Dyeing:** This is typically the most water-consuming single step. Conventional exhaust dyeing in the case plant used a high liquor ratio of about 1:11, meaning ~11 L of water per kg for dyeing . The intermediate unit's dyeing ran at 1:7 (about 7 L/kg), while the sustainable unit again used 1:6 (6 L/kg) . These differences are attributed to both machinery and dye selection: the sustainable unit possibly used machines designed to work with less water (e.g. jet dyeing machines with lower liquor requirements) and possibly high-fixation dyes that don't need as large a bath volume . Even a switch from 11 L to 7 L (intermediate) is a ~36% reduction in water use in dyeing, which is substantial given dyeing's large absolute water need.

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- **Final Rinsing (pH off-loading):** In finishing, after dyeing, a final rinse is done to achieve the correct pH and remove any remaining chemicals. The conventional process used another 7 L/kg here (1:7 ratio) . The intermediate and sustainable both performed this in 6 L/kg , again reflecting consistent use of efficient rinsing procedures (likely reusing water from previous steps or just the benefit of lower chemical load to rinse out).

The net effect of these stage-wise improvements is evident in the totals mentioned: ~46 L > 30 L > 24 L for conv → int → sust . In percentage terms, the sustainable finishing department used only about 52% of the water that the conventional one did, essentially halving the water footprint of finishing. The intermediate unit achieved roughly a 35% reduction in water usage relative to conventional. These savings are especially crucial given that water scarcity and pollution are top sustainability concerns in textiles. Reducing water usage not only conserves a precious resource but also results in proportionally less wastewater generation, which eases the burden on effluent treatment plants and reduces the pollutant load released to the environment. Indeed, the sustainable unit's practices (e.g. no de-oiling, low liquor dyeing) exemplify cleaner production techniques that many sustainable textile initiatives promote .

It's worth noting that the sustainable unit also made a *qualitative* change by avoiding certain processes (de-oiling) through upstream material choice. This suggests that sustainability should be considered at the design stage (fiber and yarn selection) – by choosing a higher-quality input, one can eliminate an entire water- and chemical-intensive step, yielding cost savings and environmental benefits. The intermediate strategy of combining steps is another important efficiency tactic accessible to many mills: scouring+bleaching in one bath is a well-documented way to save water and time. The data underscores that technological innovation and process integration are key to water conservation. The sustainable facility's liquor ratio of 1:6 across multiple steps might be approaching the practical limits of current dyeing technology for cotton, though even more radical innovations exist (e.g. foam dyeing or supercritical CO_2 dyeing, which use near-zero water). While those were not employed here, the findings show that even within conventional water-based processes, there is substantial room to reduce water intensity.

From a cost-benefit viewpoint, reducing water use has direct and indirect financial

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implications. Directly, less water means lower water bills for the factory and lower costs for heating that water (if processes run warm/hot). Indirectly, it means less wastewater to treat; many regions charge effluent fees or require on-site treatment, so cutting volume can reduce treatment chemical and energy costs. In the sustainable unit, water savings of 22 L/kg over conventional likely translate to meaningful cost savings that can partially offset its higher process costs. The intermediate unit's ~16 L/kg savings would also contribute to cost reduction, perhaps explaining why their finishing/washing cost was nil – they might have eliminated a separate rinsing step or recovered water. Moreover, these improvements carry a strategic benefit: as water regulations tighten and if water pricing or tariffs for industrial use increase (a probable scenario in water-scarce regions), the sustainable and intermediate operations are future-proofed to some extent, whereas a water-intensive conventional process might face rising costs or compliance issues. This aligns with the idea that sustainable practices, while possibly requiring investment, "improve competitiveness, decrease operational expenses, and foster accountability" in the long run.

Chemical Consumption and Management

The type and amount of chemicals used in textile finishing not only influence environmental impact (toxicity of effluents, worker safety) but can also affect cost (chemicals cost money and their use often necessitates waste treatment). Our comparative analysis found that the sustainable finishing department markedly curbed chemical usage compared to the conventional one, with the intermediate again in between. **Table 4** compiles the chemical consumption per liter of bath (or % on weight of fabric for dyes) for key substances in each process file-fpjutyrdy4sohhodgtfxkh file-fpjutyrdy4sohhodgtfxkh file-fpjutyrdy4sohhodgtfxkh file-fpjutyrdy4sohhodgtfxkh.

The general trend was conventional > intermediate > sustainable in concentration used, for nearly all inputs.

Key observations include:

- **Detergents and Solvents (De-oiling):** While not explicitly quantified in the table excerpt, it is noted that the sustainable unit completely omits the de-oiling stage, as mentioned earlier, and thus avoids any detergent or solvent usage for that. The conventional process, in contrast, uses a "substantial quantity of chemical solvents

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per kg" for de-oiling file-fpjutyrdy4sohhodgtfxkh, contributing to higher effluent load of oily waste. The intermediate uses less aggressive formulas and precise application, reducing chemical load relative to conventional , but still performs de-oiling if needed. Eliminating this stage in the sustainable model leads to a major reduction in total chemical consumption and pollution, as de-oiling chemicals can be significant contributors to COD (Chemical Oxygen Demand) in wastewater.

- **Scouring (Hydrogen Peroxide):** H_2O_2 is commonly used as an oxidizing agent in scouring/bleaching for cotton. The conventional and intermediate units both used ~3.5 g/L H_2O_2 in the scouring stage file-fpjutyrdy4sohhodgtfxkh. The sustainable unit used only 2 g/L , a reduction of about 43%. This lower requirement could be because the sustainable unit's fabric is cleaner to begin with (less natural or added impurities, since organic cotton often has less wax or contaminants), or because they might use auxiliary chemicals or enzymes that enhance scouring efficiency, allowing a lower peroxide dosage. Another possibility is that the sustainable process might combine scouring with bleaching in one step at a optimized chemical balance, therefore needing less of each.
- **Bleaching (NaOH):** Sodium hydroxide is often used in scouring/bleaching to saponify fats and aid in cleaning cotton. The conventional and intermediate processes used 3 g/L NaOH, whereas the sustainable used 2.5 g/L . A smaller reduction (~17%) here suggests even the sustainable process still relies on alkaline treatment but perhaps slightly milder. Combined with peroxide, the overall oxidative-alkaline strength is a bit lower in sustainable, which could be due to better initial fabric quality or a trade-off accepted to reduce damage to fibers.
- **Neutralization (Acetic Acid):** After bleaching, acetic acid is used to neutralize excess alkali. The conventional unit needed about 2 g/L, intermediate 1.5 g/L, and sustainable only 1 g/L . This descending order correlates with how much alkali was used prior (conventional had more to neutralize). It also suggests the sustainable unit's careful control of pH and use of just sufficient acid, possibly aided by pH monitoring technologies. Reducing acid usage is beneficial as it lessens the salt load (neutralization produces sodium acetate in effluent).

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- **Enzymatic Treatment (Cellulase):** Cellulase enzymes are often applied to improve fabric hand (bio-polishing) by removing protruding fibers. The conventional process used ~1.5 g/L of enzyme, intermediate ~1 g/L, whereas the sustainable unit used none (0 g/L) . The sustainable facility apparently skipped the enzyme step – this could be because they might achieve fabric smoothness through other means (e.g. using combed cotton that is already smooth, or high-quality knitting that doesn't need bio-polish). It could also be a conscious choice to avoid enzymes if not necessary, as enzymes, while relatively eco-friendly compared to chemicals, still add cost. The intermediate did use some enzyme, indicating a partial adoption of that quality-enhancing step, while the conventional used it possibly to improve their lower-quality fabric's appearance (ironic, as conventional uses both harsh chemicals and then enzymes to fix issues).
- **Dyeing (Dye Concentration):** The dye concentration is given as a percentage on weight of fabric (OWF). The conventional unit used about 7% OWF dye, whereas intermediate and sustainable each used 6%. This implies that for the same shade depth, the conventional process required more dye – likely due to lower fixation efficiency (more of the dye doesn't stick and gets washed out) or the use of less advanced dyes. The sustainable and intermediate possibly used better dyestuffs or techniques (like optimized pH, salt, or temperature profiles) to get the same color with ~15% less dye. In practical terms, using less dye not only saves on dye cost but also means less colored effluent (lower treatment burden). The fact that intermediate and sustainable are equal here suggests that even partial improvements in dyeing (shorter liquor, better dye selection) can yield this benefit.
- **Final Neutralization (**Acetic acid in pH off-loading): In the last rinse, a bit of acetic acid ensures neutral pH of fabric. Conventional and intermediate used about 1 g/L, sustainable used 0.5 g/L file-fpjutyrdy4sohhodgtfxkh. Again, half the acid consumption in sustainable indicates less alkali to neutralize or finer control. It's a small quantity but symbolically shows the trend of reduction.

Overall, the sustainable finishing department managed to either eliminate or substantially reduce chemical inputs at every stage, focusing only on what was necessary. Using bio-based or less toxic alternatives is also part of their strategy (e.g. possibly using peroxide

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activators or biodegradable scouring aids) file-fpjutyrdy4sohhodgtfxkh. The intermediate unit adopted some of these measures (combined processes, enzymes, etc.) hence it also shows lowered chemical usage compared to conventional, though not as dramatically as the sustainable one. The conventional unit represents typical practices: heavy use of chemicals to force outcomes (strong scour, full bleach, etc.) and then more chemicals to counteract side effects (more neutralizer, etc.), illustrating the inefficiencies and higher pollution potential of the traditional approach.

From an environmental standpoint, reduced chemical usage means the effluent from the sustainable process is significantly less polluted. For instance, not using certain chemicals (like detergents or high salt from dyes) can reduce the chemical oxygen demand (COD) and toxicity of the wastewater. The 0 g/L cellulase in sustainable also means no enzyme proteins going to waste (which, while not highly toxic, still contribute to organic load). Moreover, sustainable units often aim to use safer chemicals – the dataset doesn't directly show chemical substitutions (e.g. if sustainable used a different bleaching agent or a sequestering agent), but one can infer there may be differences beyond just quantity. The presence of certification like OEKO-TEX in the sustainable unit (as hinted in other context) indicates their chemical inputs are vetted for toxicity. The intermediate's chemical profile suggests some green chemistry adoption (e.g. lower dye and acid use).

Economically, chemical savings translate to cost savings on procurement of those chemicals. If a sustainable process uses, say, 30% less chemicals by weight, that can directly lower variable costs. Additionally, many sustainable chemicals (like high-fixation dyes or organic inputs) might be more expensive per unit, but used in lower quantities or with better efficiency, potentially balancing out costs. Another economic angle is regulatory: as environmental regulations tighten, plants using hazardous chemicals might face higher compliance costs (e.g. needing expensive effluent treatment to remove those chemicals). Using fewer and milder chemicals, the sustainable unit likely has an easier time meeting discharge standards and might avoid investments like advanced chemical treatment stages. This is in line with the idea of "closed-loop systems and substitution of hazardous substances with safer alternatives" to reduce environmental impactThe sustainable unit's practices exemplify this by using less NaOH and H_2O_2 (minimizing oxidative damage and hazardous byproducts) and by presumably using certified dyes (the

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text mentions use of OEKO-TEX® certified chemicals as crucial for sustainable.

It's also notable that despite using milder chemistry, the sustainable unit still achieved necessary performance (e.g. good scouring, adequate dye depth). Literature supports that innovations like enzymatic scouring or combined processes can maintain fabric quality while reducing chemical load . Our findings reinforce that real factories can implement such measures effectively.

Cost-Benefit Implications and Sustainability Trade-offs

The comparative results above paint a clear picture: the *sustainable finishing unit* attains superior environmental performance – drastically cutting water usage and chemical usage – but incurs a higher immediate production cost per unit output. The *intermediate unit* shows that a middle route can gain a large share of the environmental benefit at a more modest cost increase. To fully understand the implications, we must weigh the short-term costs against long-term benefits and consider external factors like market demand and policy.

Financial Trade-offs: On a purely cost basis, producing a shirt in the sustainable way was roughly 2–3 times more costly than in the conventional way (depending on whether looking at fabric stage or finished garment). This kind of increase is non-trivial for manufacturers, especially in cost-sensitive segments of the market. However, the analysis also shows that the sustainable model incorporated a substantially higher profit margin, suggesting that it targets a premium market segment where consumers pay more for sustainability. If the market accepts the higher price (as current trends indicate for eco-labeled products), the business case for sustainable production strengthens. In essence, the additional cost can be passed on to the end consumer who is buying not just a product, but its sustainable story. This is evidenced by the sustainable unit's margin, which positions sustainability as a *value-add* rather than a pure cost. Brands like Patagonia or Eileen Fisher in the apparel industry, for example, have successfully commanded higher prices by focusing on ethical and sustainable production, validating this approach in practice.

For the intermediate unit, the costs were only moderately higher than conventional, yet it presumably can market some improved sustainability features. This suggests that many improvements (like water savings and partial chemical management) can be made with little cost penalty – often through process efficiency which sometimes

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even saves money (e.g. combining steps reduces energy and labor time). Indeed, eco-efficiency studies in textile mills have found that cleaner production measures can improve both environmental and economic performance by cutting waste file-fpjutyrdy4sohhodgtfxkh. Our intermediate case likely reflects such low-hanging fruits: they cut out one process (finishing/washing) entirely, saving cost, and reduced water and chemical use, which also saves costs, thereby balancing out expenditures like slightly better dyes.

Long-term and Hidden Benefits: Sustainable practices often yield benefits that are not immediately captured in a simple cost per unit calculation. For example, using 22 liters less water per kg means the sustainable factory might be less vulnerable to water shortages or price hikes. If a drought hits or water tariffs increase, the conventional facility might face production cuts or higher bills, whereas the sustainable one can continue relatively unhindered. Similarly, by using fewer hazardous chemicals, the sustainable unit lowers the risk of non-compliance with environmental regulations and avoids potential fines or shutdowns. It also improves worker safety (less exposure to caustic chemicals), potentially reducing healthcare costs or increasing labor productivity/morale. These are part of what could be termed the "sustainability dividend" – benefits that accrue over time. As one study noted, early investments in sustainable technology and materials, despite higher upfront costs, bring long-term advantages like reduced resource use, improved brand reputation, and fewer regulatory issues, justifying the economic case for sustainability . Our findings support this: the sustainable unit's resource thriftiness will translate to ongoing savings and resilience. Additionally, its strong brand positioning (evidenced by high profit per shirt) indicates a reputational advantage that can secure market share and even allow expansion into new markets that demand compliance with green standards (e.g. European buyers with stringent RSL – Restricted Substances List – requirements).

Environmental and Policy Context: The environmental improvements measured (roughly 50% water saving, significant chemical reduction, etc.) directly contribute to key sustainability goals. They help in tackling the most "vulnerable" aspect of textile sustainability – the environmental aspect. In the context of Bangladesh's knitwear sector, for example, an index-based assessment found the environment to be more vulnerable

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(SVI=0.632) than economic or social aspects, underscoring the urgent need to reduce environmental impact. A sustainable finishing process like the one studied addresses this head-on by slashing water use and pollution, thereby mitigating one of the industry's largest environmental vulnerabilities (water pollution). If more factories adopted such practices, the cumulative reduction in water extraction and chemical discharge would be immense, contributing to SDGs on clean water (SDG6), responsible consumption/production (SDG12), and climate action (SDG13, since less energy used for heating water etc. means lower emissions).

Policymakers are increasingly pushing for these outcomes. The EU's recent moves toward a circular economy and sustainability due diligence mean that supply chains will likely be required to demonstrate reduced environmental footprint. In the near future, factories with conventional processes might find themselves unable to sell to certain markets or having to invest heavily in end-of-pipe solutions to treat wastewater and emissions. On the other hand, factories that have proactively invested in cleaner processes will meet such requirements more easily and may even receive incentives (government grants, better financing terms, etc.). Thus, the cost of not adopting sustainable practices could grow – an important consideration for the conventional-minded managers. As one review noted, companies that do not adapt risk not only legal penalties but also losing market standing. In this sense, the higher cost reported for the sustainable unit can be seen as the true cost of responsible production, one that eventually might not be optional but mandatory.

Future Outlook – Technology and Scale: As sustainable technologies advance and become more common, their costs are likely to decrease. For example, low-liquor-ratio machines and water recycling systems might be expensive now, but if industry adoption increases, economies of scale and technical improvements can reduce those costs. The same goes for sustainable raw materials: the more demand for organic cotton, the more supply will scale up and potentially lower the price premium. The intermediate unit today might become the conventional of tomorrow as certain sustainability measures turn mainstream. Our analysis suggests that even incremental steps yield substantial benefits, so an industry-wide move toward the intermediate scenario could already achieve a large portion of the environmental benefit with marginal cost increases (which might be absorbed by slight price adjustments or efficiency gains). Meanwhile, the fully sustainable

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scenario sets the benchmark for what is achievable and will likely become more attainable cost-wise in the future.

Recommendations: Manufacturers should view sustainable processing not just as an added cost, but as an investment – one that can pay off through multiple channels: resource savings, market access, brand differentiation, and risk mitigation. Tools like Life Cycle Costing (LCC) and integrated sustainability accounting can be used to evaluate projects by considering long-term savings and avoided costs, not just immediate expenditures file-fpjutyrdy4sohhodgtfxkh. We recommend that companies perform such holistic assessments when considering upgrades (for instance, calculating how much water/energy cost would be saved over 5 years by installing a low-liquor dyeing machine, and how that compares to its capital cost). Often, the payback periods can be reasonable when all factors are included.

For policymakers and industry bodies, facilitating the transition is crucial. This could include providing financial incentives (loans, subsidies) for sustainability upgrades, disseminating best practices (like the water-saving and chemical reduction strategies observed here), and setting progressive regulatory standards that nudge conventional operators to improve. Certifications and labeling (e.g. bluesign®, OEKO-TEX®, GOTS) also help create market recognition for sustainable production, which in turn supports the price premium that makes it financially viable file-fpjutyrdy4sohhodgtfxkh. The data from this study strengthens the argument that sustainable production is not only environmentally necessary but can be aligned with business profitability, especially if external support and informed management decisions are in place. In conclusion, the cost implications for sustainability in knitwear finishing are nuanced: there are higher costs per unit at face value, but they come with significant reductions in environmental impact and with opportunities for recovery via market premiums and long-term savings. The intermediate path offers a practical route for many manufacturers to start the journey, capturing many benefits with manageable cost increases. The fully sustainable model, while presently the costliest, delivers the best environmental outcomes and is likely to become more cost-effective over time, particularly as stakeholders across the value chain increasingly valorize sustainability. The following conclusions synthesize these findings and insights for wider application.

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Conclusion

Sustainable fabric finishing in the knitwear industry markedly improves environmental performance – cutting water usage, lowering chemical pollution, and supporting corporate social responsibility goals – at an identifiable cost premium. By quantitatively comparing a conventional, an intermediate, and a sustainable finishing department for a standard knitted garment, this study illuminates the trade-offs and synergies between economic and environmental objectives. The conventional process, while cheapest, was resource-intensive: it used the most water (≈46 L/kg) and chemicals, burdening the environment and potentially incurring hidden costs in effluent treatment and regulatory compliance. The sustainable process demonstrated that it is possible to reduce water consumption by nearly half (to 24 L/kg) and significantly curtail chemical use (e.g. eliminating certain steps and toxic inputs) through innovations like low-liquor-ratio processing, process integration, and greener chemistry. These changes align the production with sustainable development pathways, mitigating some of the most pressing impacts of textile manufacturing. The intermediate process achieved a large portion of these gains with only moderate cost increase, highlighting that many cleaner production techniques are accessible and economically sensible as first steps (such as combining scouring/bleaching, or optimizing dye recipes).

In terms of cost implications, the sustainable finishing route did entail higher direct costs – roughly doubling the cost per kg of fabric and more than doubling per garment cost compared to conventional methods in our case. However, crucially, these costs should be viewed in the context of value addition and future readiness. The sustainable unit's ability to command premium pricing indicates that there is a willing market for sustainably made apparel, allowing manufacturers to recoup investments in sustainability. Moreover, when factoring in long-term benefits – reduced water and energy bills, avoidance of compliance penalties, enhanced brand equity, and access to discerning markets – the investment in sustainability proves to be a prudent strategy rather than a financial sacrifice file-fpjutyrdy4sohhodgtfxkh file-fpjutyrdy4sohhodgtfxkh. The findings suggest that what appears today as an "extra cost" for sustainability can tomorrow become a cost savings or revenue driver as external conditions evolve (for instance, if carbon or water pricing is implemented, or if consumers increasingly favor sustainable products). The study also underscores the importance of

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supportive measures and continuous improvement. For manufacturers at the start of the sustainability journey, adopting an incremental approach – like the intermediate scenario – can yield significant improvements without straining budgets. Simple measures like reusing water from one process in another, switching to better process chemicals, or improving raw material quality can often pay for themselves. As confidence and capabilities grow, firms can then progress towards the fully sustainable model. Policy interventions can accelerate this progression by lowering the barriers: e.g. financial incentives for water-efficient machinery, stricter discharge standards that level the playing field by internalizing environmental costs for all, and technical assistance programs to share knowledge on best practices (such as those observed in the sustainable unit here). Given that environmental vulnerability remains high in textile-producing regions, such interventions have socio-economic justification as well.

In conclusion, achieving sustainability in textile finishing is a feasible and forward-looking endeavor. The quantitative assessment provided by this research demonstrates that while sustainability has its price, it also has its payoffs – in environmental protection, compliance, and even profit when leveraged correctly. The fabric finishing department, often a hotspot of water and chemical use, can become a model of eco-efficiency with the right investments. Companies that embrace this will not only contribute to a more sustainable fashion industry but also ensure their operations are resilient and competitive in a future where sustainability is no longer optional but essential. We recommend that knitwear manufacturers and stakeholders use these insights to inform strategic decisions, balancing cost with sustainability through a lens of innovation and responsibility. By doing so, the industry can progress toward a circular, low-impact model that secures both the planet's health and business viability for years to come.

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