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## Objective Quantitative Assessment of Worn Clothing Soils

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Keywords: Cleanliness, body soils, ozone depletion, human sebum

Invariably, all apparel Life Cycle Analyses point to washing and drying as primary contributors to the environmental footprint of a garment (Laitala, Klepp, & Henry, 2017). Major impacts notably include energy and water consumption, global warming potential, ozone depletion and eutrophication (Allwood, Laursen, & Bocken, 2006; Laitala, Boks, & Klepp, 2011). As a result, recent developments in laundry equipment have focused on energy and water efficiency. One major challenge is that as laundering becomes more energy- and water-efficient, there is no objective way to measure cleaning performance (Lin & Iyer, 2007; Rajaganesh & Krifa, 2017). Therefore, the objective of this research is to evaluate a quantitative method to measure garment cleanliness, with a focus on soils accumulated upon contact with the human body.

*Rationale & Approach* Human sebum, a sebaceous secretion of the skin, is a major source of organic soil in worn clothing (Chi & Obendorf, 1998). In particular, squalene, oleic acid, linoleic acid, and triolein are abundant in worn garments (Bowers & Chantrey, 1969; Chung & Seok, 2012). These oily contaminations also serve as a nourishing medium on which microorganisms thrive, leading to the development of malodor in clothing (Chung, 2012). Ozone acts as an effective oxidant with unsaturated organic compounds such as those present in human skin lipids (Wisthaler & Weschler, 2010). In the human sebum, squalene has been confirmed as a “major scavenger of ozone” in reactions occurring between the atmosphere and the human skin environment (Wisthaler & Weschler, 2010). Thus, our approach is to capitalize on the affinity between ozone and the oily organic compounds found in clothing to quantify the level of soiling by observing the reaction of ozone with the soiled garments, i.e., by quantifying the rate of ozone depletion in presence of a soiled garment.

*Methods* Single jersey 100% cotton swatches were loaded with varying concentrations of sebum solutions prepared according to ASTM D4265, and to Wertz (2009). Sebum-loaded samples along with sebum-free experimental controls were exposed to ozone in closed stainless steel reaction chambers. Ozone concentration of the air exiting the chamber after contact with the sample was monitored and recorded as a function of time. The corresponding ozone depletion pattern is consistent with the theoretical exponential decay function, i.e., expressing  $O_3$  concentration  $C$  as a function of time  $t$  according to the following equation:

$$C(t) = C_0 e^{-kt} \quad (1)$$

where  $C_0 = C(0)$  is the initial concentration, and  $k$  is a positive constant referred to as the exponential decay constant. Logarithmic transformation of the decay model provides:

$$\ln[C(t)] = -kt + \ln(C_0) \quad (2)$$

where  $-k$  is the slope of the ozone concentration natural logarithm as a linear function of time. Based on this equation,  $k$  represents a measure of the rate of ozone depletion. Given the reactivity of ozone with the oily substances in the sebum, it is expected that the presence of those compounds would accelerate the ozone decay reaction and result in a faster depletion rate. Thus,

the primary research question tested in this experiment is whether there is a relationship between the level of sebum soiling on the fabric samples and the corresponding ozone depletion rate  $k$ .

**Results and Discussion** The exponential decay model above was applied to the results obtained on fabric samples containing varied amounts of sebum. Figure 1 depicts the logarithmic plots for five such samples, including a sebum free control. The data series legend on Figure 1 reflects sebum emulsion add-on in milligrams on a fabric samples averaging 2.4 g in weight.

It is apparent from the results in Figure 1 that the incorporation of the soil emulsion onto the fabric swatch resulted in a sizable acceleration of ozone depletion compared to the unsoiled control. Even with the lowest add-on concentration, the observed  $k$  value is almost double that seen with the control sample. Differences in  $k$  values among soiled samples with varied amounts of sebum are also detected (Figure 1). However, variations of the logarithmic slope between non-null sebum contents appear of lower magnitudes. As a result, the general pattern of the  $k$ -vs-soil-content curve is non-linear (Figure 2). In fact, the pattern seen in Figure 2 appears segmented with a rapid increase in  $k$  attributed to the presence of soiling in any amount (compared to the control), followed by a slow increase as further soiling increases.

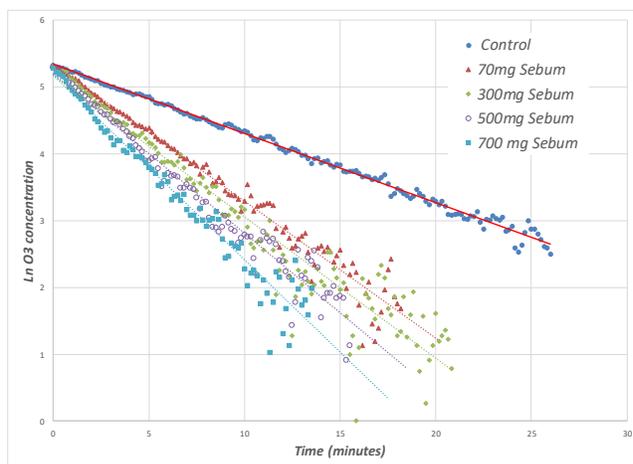


Figure 1: Logarithmic plots of the ozone decay curves for fabric samples with varied soil amount.

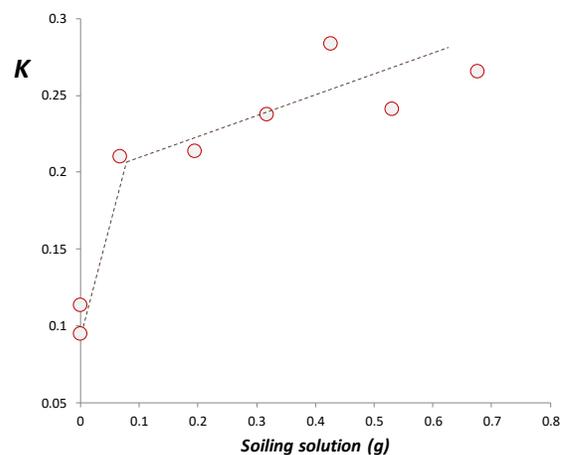


Figure 2: relationship between ozone decay rate  $k$ , and soil add-on

**Conclusion** The results obtained are in support of the primary hypothesis put forth in this research, i.e., the presence on fabric of the unsaturated compounds found in skin lipids accelerates ozone decay. Thus, it appears feasible based on our result to detect the presence of skin oily soils on garments using the variation of ozone decay rates, provided that adequate baseline is established using contamination-free controls. Beyond the detection of sebum compound presence, distinguishing between different quantities of contamination requires further research given the non-linear segmented pattern of the  $k$ -vs-soil-content curve. Calibration with a better control of  $k$ -value variability is needed to achieve adequate distinction between different levels of contamination.

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