CLEANING OF FOOD -
Alternatives to present water use patterns

John M. Krochta and Richard J. Bellows*

Cleaning is probably the most widely used of all food processing operations, ranging in significance from the major processing step to a simple housekeeping activity. Raw products must be cleaned of contaminants accumulated during growth, harvest, and transport; processing equipment and facilities must be kept clean to prevent recontamination of the food. This paper emphasizes cleaning of the food itself, the so-called "soft surface cleaning" in contrast to the cleaning of equipment and facilities ("hard surface cleaning").

Cleaning is a separation and transport process. Its function is to 1) separate soil from the substrate (material being cleaned) and 2) transport the soil away in the cleaning medium to prevent recontamination of the clean surface. In this regard "soil" is defined generally as "matter out of place" (Jennings, 1965). Field soil, trash, insects, pesticides, and plant exudates are of concern in cleaning raw foods.

Mechanical harvesting has increased the cleaning problem because of increased soil contamination and product breakage. As an example, soil loads on machine-picked tomatoes have been found close to 2%, with 10% of the soil present in the difficult-to-remove smear form (Mercer, 1967). It is not unusual for a canner to receive loads of tomatoes having 30% broken fruits. This compares with approximately 10% damaged with handpicking. Broken fruit contributes to the plant exudate soil and can aggravate insect contamination problems. Broken fruit and heavy soiling have increased effluent strengths and volumes as the food processor has attempted to clean raw product entering the plant solely through the use of greater amounts of water.

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The Authors are, respectively, research chemical engineer and NRC-ARS postdoctoral research associate with the USDA Western Regional Research Laboratory, ARS, Berkeley, California.

We have explored factors affecting the nature of soiling and cleaning in attempting to reduce water consumption and pollution from this process. For soiling, this includes the effect of moisture content and fruit exudate on soil deposition and adherence. For cleaning, this includes the effect of water, detergent solution, foam, nonpolar liquid, and a water nonpolar liquid suspension as cleaning media. The degree of soil removal in terms of water used is of interest.

Development of Theory

Soiling is a spontaneous process (Jennings, 1965) which can be represented as

$$\text{Free Soil} \rightarrow \text{Deposited Soil};\ \Delta G = -\ N \text{ calories.} \qquad (1)$$

This process is shown schematically in Figure 1. There is a negative change in free energy, ΔG. Therefore, a certain amount of energy is always required to produce a clean surface. For soils (2) which wet a surface (1), the change in free energy for soiling in air or other media (3) is

$$\Delta G_{\text{SOILING}} = A(\gamma_{12} - \gamma_{13} - \gamma_{23}) \qquad (2)$$

where γ is surface tension and A is area of soiling. For situations of this type with a measurable contact angle, Θ, the Young and Dupre equation (Adamson, 1967) may be used:

$$\gamma_{13} = \gamma_{12} + \gamma_{23}\ (\text{COS}\ \Theta) \qquad (3)$$

Combining equations (2) and (3), one obtains

$$\Delta G_{\text{SOILING}} = A[-\gamma_{23}\,(1 + \text{COS}\ \Theta)] \qquad (4)$$

This shows that for any Θ less than 180°, soiling will occur spontaneously. For all real cases, soiling will therefore occur; and any factor which reduces Θ will enhance the soiling process. These factors must be identified, and if possible be controlled during growth, harvest, and transport so that spontaneous soiling is minimized prior to final cleaning for preservation. We have evaluated the effect of soil moisture content and fruit exudate, two primary factors affecting soil deposition and adherence and hence the cleanability of raw product prior to processing.

The basic system of interest here consists of a waxy surface in air (e.g., a tomato) which is soiled with wet clay particles having free surface moisture. The soil is assumed to have the wetting properties of water and the waxy surface is assumed to have the properties of paraffin in order to estimate the free energy change during soiling. This model assumes that the adhesion of the wet clay soil to the waxy surface is primarily due to the continuous wax-water interface formed by the free water, rather than point-

$$\Delta G_{\text{SOILING}} = -\text{N CALORIES}$$

$$\Delta G_{\text{SOILING}} = A\,[\gamma_{12} - (\gamma_{13} + \gamma_{23})]$$

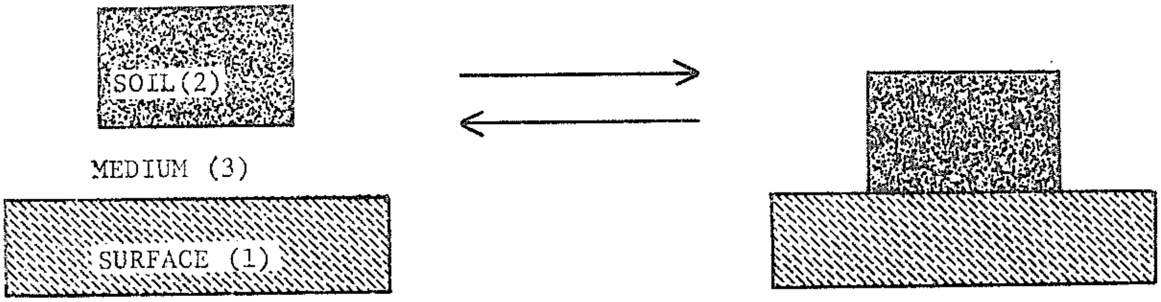

Figure 1. Thermodynamics of soiling

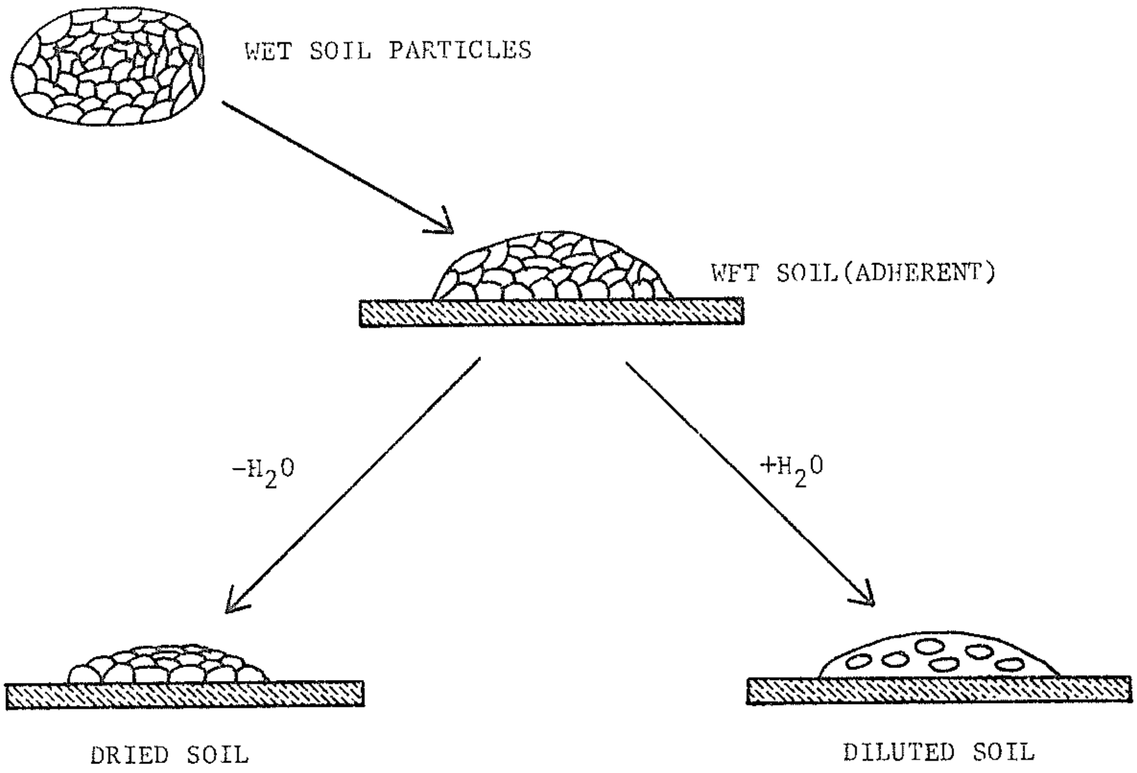

Figure 2. Wet soil on a waxy surface

wise wax-clay adhesion, such as with a totally dry soil. Inserting the necessary surface tensions from Table 1 into equation (2) yields:

$$\Delta G_{\text{SOILING}}^{\text{AIR}} = A(51 - 26 - 73) = -48 \text{ A ergs/cm}^2 \tag{5}$$

Cleaning is the reverse of soiling. As a result the change in free energy for removing a soil (2) from a surface (1) in a cleaning medium (3) is

$$\Delta G_{\text{CLEANING}} = A(\gamma_{13} + \gamma_{23} - \gamma_{12}) \tag{6}$$

or

$$\Delta G_{\text{CLEANING}} = A[\gamma_{23}(1 + \cos \Theta)] \tag{7}$$

Thus, removing wet soil from a waxy surface in air would require an energy input of

$$\Delta G_{\text{CLEANING}}^{\text{AIR}} = A(26 + 73 - 51) = 48 \text{ A ergs/cm}^2 \tag{8}$$

However, placing the soiled surface into a different medium results in a different free energy of cleaning. The surface tension values of Table 1 give the following free energy change for cleaning in a water medium:

$$\Delta G_{\text{CLEANING}}^{\text{WATER}} = A(51 + 0 - 51) = 0 \tag{9}$$

The free energy change calculated for cleaning in a paraffin oil medium is also zero:

$$\Delta G_{\text{CLEANING}}^{\text{PARAFFIN OIL}} = A\ (0 + 51 - 51) = 0 \tag{10}$$

Table 1. Interfacial Tensions, γ, for several interfaces (Fowkes, 1964)

Interface	γ, ergs/cm^2
Water-air	73
Paraffin wax-air	26
Paraffin oil-air	29
Paraffin wax-water	51
Paraffin oil-water	51
Paraffin wax-paraffin oil	0
Water-water	0

Determined using Fowkes approximation for interfacial tension with γ = 22 ergs/cm^2 for water.

It can be seen that waxy surfaces wetted with clay soils are more easily cleaned in water than air. However, our analysis also shows the potential equal effectiveness of a paraffin-oil cleaning medium. A paraffin oil cleaning medium would have the benefit of keeping the soil in a concentrated form, since it would settle in a liquid paraffin, like (nonpolar) cleaning medium rather than disperse. The decanted paraffin oil may be easier to clean for reuse. Interestingly, equation (7) shows that $\Delta G = 0$ for cleaning in water ($\gamma_{23} = 0$) and in liquid paraffin ($\Theta = 180°$). Liquids intermediate in polarity with $\gamma_{23} > 0$ and $\Theta < 180°$ give a $\Delta G_{\text{CLEANING}} > 0$ for the wetted clay soil on a waxy surface.

The assumption that soil has the wetting properties of water, which was used in this model, is hardly ever realized completely in practice. Thus, although ΔG for cleaning is reduced by immersion of a soiled waxy object in water, some energy input is usually required, i.e., $\Delta G^{\text{WATER}}_{\text{CLEANING}} > 0$. The energy requirement would increase as the moisture content of the soil decreased. With the exception of a completely watery soil, some energy would also be required in an oil-cleaning medium; i.e., $\Delta G^{\text{OIL}}_{\text{CLEANING}} > 0$. Nonetheless, the model shows the potential of an oil-cleaning medium. The analysis also suggests an oil-water suspension cleaning medium, with the water available both to help cleaning and to hydrate the soil.

Such an analysis also shows the advantage of adding detergents to aqueous cleaning media, since they reduce γ_{13} and γ_{23}. The result is also a reduction of $\Delta G_{\text{CLEANING}}$. We have attempted to compare the cleaning effectiveness of water, a detergent solution, a foam, a non-polar liquid, and a suspension of water and a non-polar liquid.

Tomatoes Used for Experiment

We selected tomatoes for the study because of their economic importance and the large amount of water consumed and effluent generated in their cleaning. Soiling and cleaning experiments were performed in most cases on Mexican-grown, store-bought tomatoes. Evaluation of paraffin oil and water-paraffin oil suspension cleaning media was performed using store-bought cherry tomatoes.

Experimental soil was obtained by slurrying silty-loam soil in water, discarding soil which settled within the first 20 minutes, and collecting the remaining suspended soil by further settling and/or centrifugation. The fine clay obtained by prolonged settling and centrifuging was expected to adhere most strongly to tomatoes and to simulate the fine soil a tomato would pick up during mechanical harvesting.

Water or tomato juice was added to the heavy soil slurry (39-42% water) to achieve any desired total moisture content soil. Tomato juice was prepared by cutting, mashing, and then screening ripe tomatoes through 10- and 35-mesh screens.

Advancing contact angles were determined by pipetting a 0.02-ml drop of wet soil onto a tomato surface and measuring directly. Receeding contact angles were determined after quickly flattening the wet soildrop into the tomato surface with a metal spatula and then allowing the drop to reform. All measurements were made with a Model No. A-100 Goniometer (Rame-Hart Inc., Mountain Lakes, N.J.).

Moist soil was applied for cleaning experiments with the fingertip of a rubber glove by smearing the soil as consistently as possible over a 1-in-sq area for the regular-size tomatoes and a 3/4-in-sq area for the cherry tomatoes.

Cleaning experiments with regular-sized tomatoes were performed in a seven-liter agitated bath, while experiments with cherry tomatoes were performed in a one-liter beaker with agitator. Experiments were performed in triplicate and results average.

Soil residues were determined by allowing the soil to dry, scraping the residual soil from the tomato surface, and then weighing the soil.

Foam used was generated with a Model 310 Foam Generator with a No. 1.5 feed pump (Waukesha Foundry Co., Inc., Waukesha, Wis.) operating at 3,200 rpm. An 0.3% solution of Duponol C (sodium lauryl sulfate) (E.I. Du Pont de Nemours and Co., Wilmington, Del.) in water was used to produce a foam of 0.1 g/ml density. A four-liter container was filled with the foam and soiled tomatoes dropped into the container where they remained for one hour before being removed for determination of soil residue. Foam treatment was compared with washing soiled tomatoes in stagnant water and 0.3% aqueous solution of Duponol C for one hour.

Effect of Soil Moisture and Tomato Juice

Figure 2 shows the different situations encountered in the soiling of the waxy tomato surfaces. When soil has no free surface moisture, adhesion is by point-wise clay wax contact. Thus the soil adheres weakly and any soil which does adhere is easily removed. When the soil exists essentially as a solution in water, the soil tends to assume the properties of water with a large surface contact angle which is indicative of easy cleaning. Between

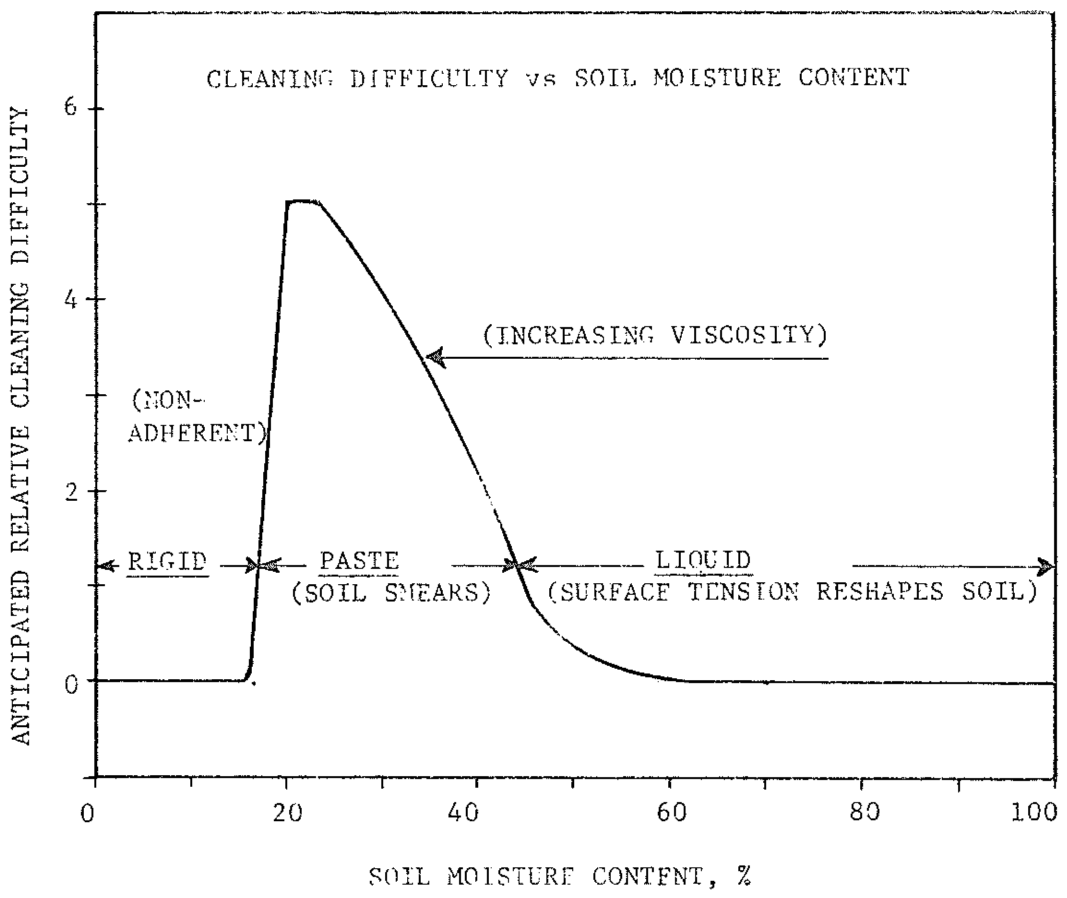

Figure 3. Physical and Soiling Properties of soils with indicated water content.

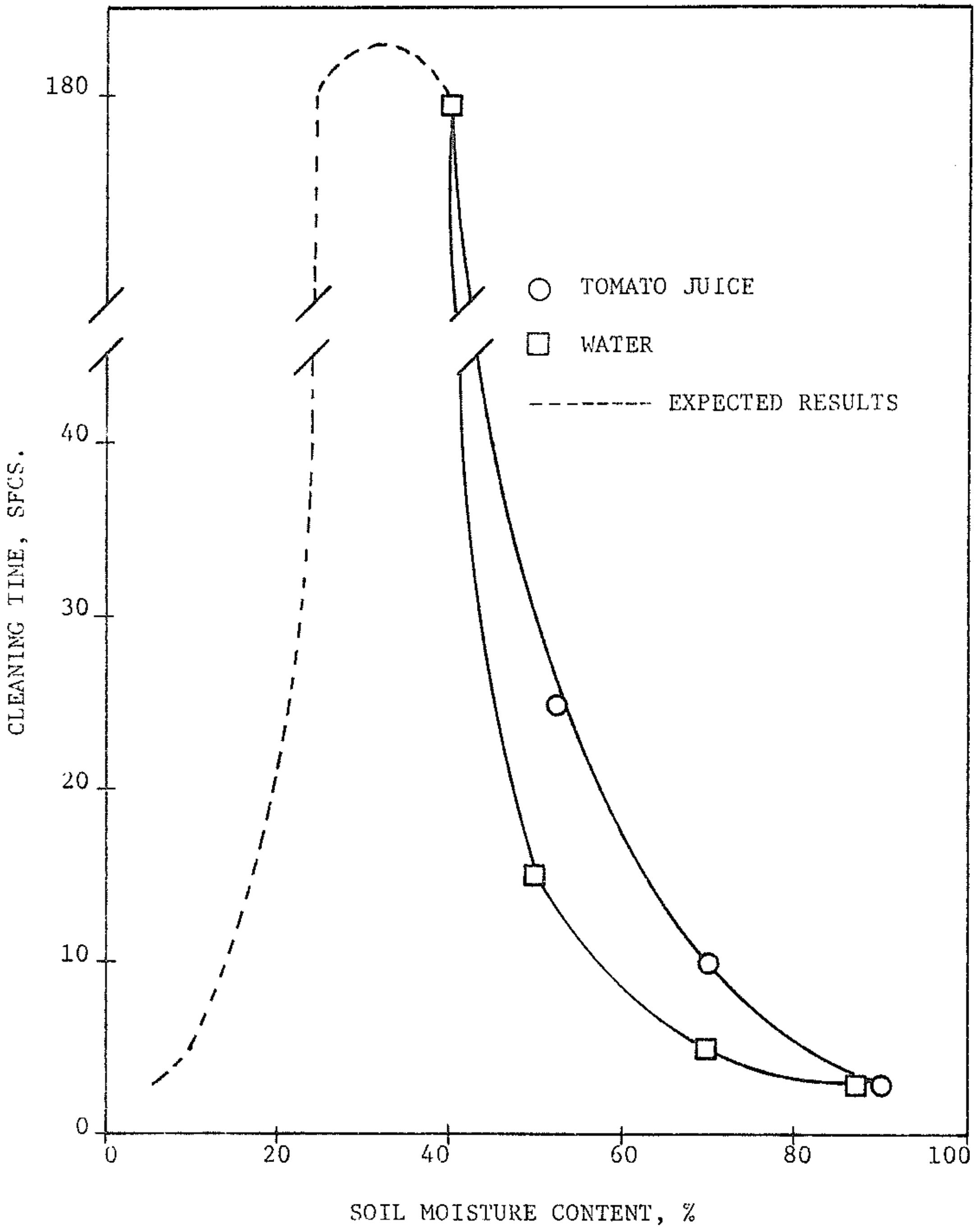

Figure 4. Cleaning times for tomatoes smeared with soils of various water and tomato juice content. Tomatoes cleaned immediately after soiling.

these extremes exists a paste-like soil which smears on the waxy tomato surface quite easily and has a very low contact angle.

Table 2. Contact Angles for water, soil-water, solutions and tomato juice on tomato surfaces

	Contact angles	
	Advancing	Receding
Water	90°	60°
80% moisture soil	89°	55°
70% moisture soil	88°	45°
Tomato juice	75°	16°

Table 2 shows the effect of decreasing moisture content on the contact angle of a soil on a tomato surface. At lower moisture contents, the soil eventually becomes a paste of high viscosity with a very small receding contact angle. Table 2 also shows the small receding contact angle of tomato juice, thus suggesting its role in promoting soil smearing on tomoto surfaces.

Figure 3 shows the observed soil characteristics and anticipated relative difficulty of soil removal for soils over the entire range of moisture contents. A dry, particulate, rigid soil exists in the range 0-20% moisture. Then, rather abruptly, a viscous, pasty soil forms with increasing moisture content which adheres strongly and is difficult to remove. As moisture content increases further, the soil loses its pasty character and eventually becomes a watery solution which is much easier to remove. Figure 4 shows some actual cleaning data obtained in an agitated bath. The cleaning time dependence on soil moisture content is clearly indicated. The effect of tomato juice in the soil is apparent, as it definitely promoted soil smearing and increased cleaning times. (Data for tomato juice is for tomato juice added to a 40% moisture soil to bring soil up to indicated moisture content.) The low expected relative cleaning difficulty of soil below 20% moisture indicated in Figure 4 reflects the nonadhering properties of this dry soil.

Figure 5 shows the total cleaning curve for a 52% moisture content soil. Soil residues are shown as a function of time. Cleaning was performed immediately after soiling, and each data point represents separately soiled tomatoes. The data approximates a semilog plot, suggesting first-order kinetics for soil removal when cleaning occurs soon after soiling.

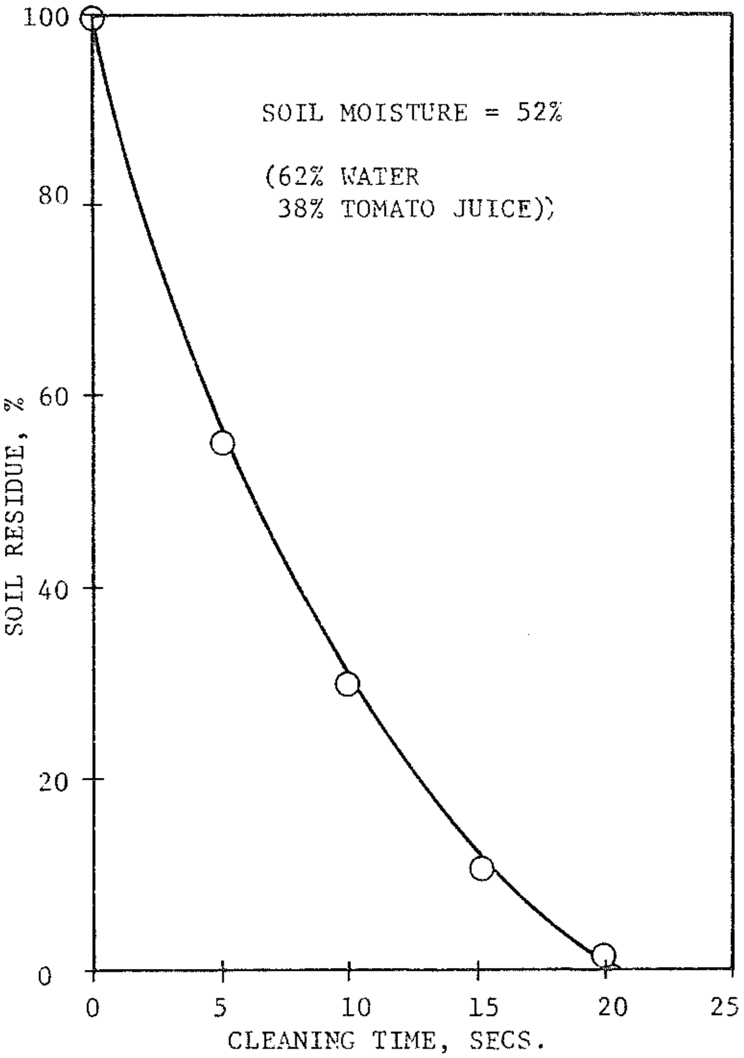

Figure 5. Soil residue on tomatoes after cleaning for specified times. Tomatoes cleaned immediately after soiling.

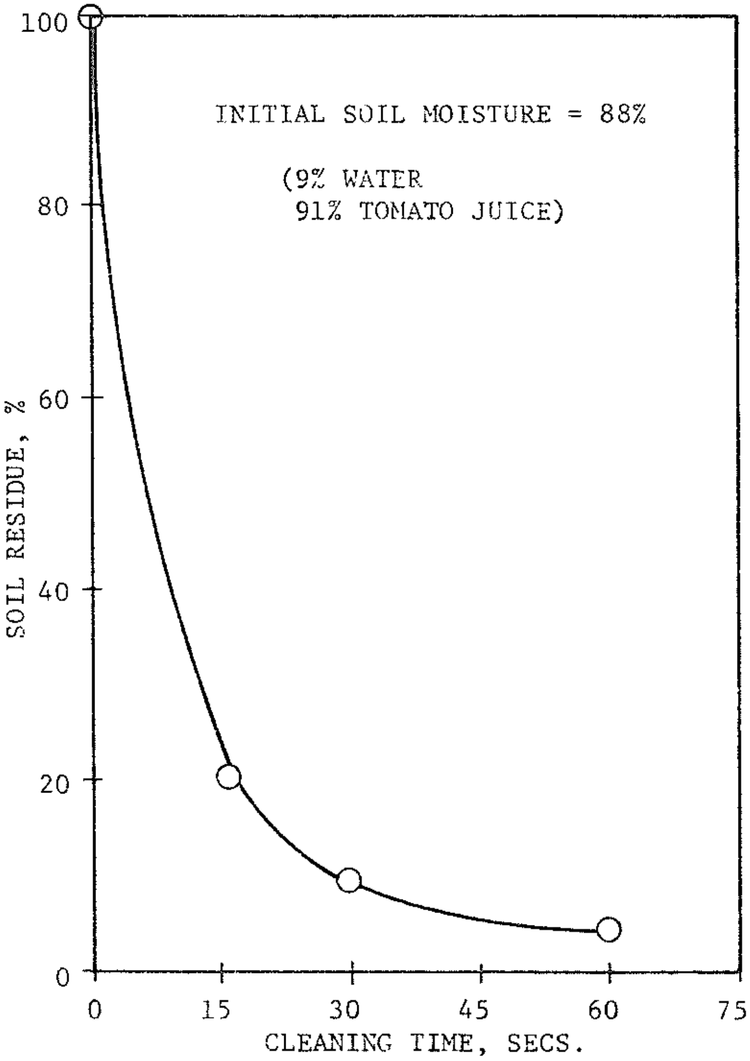

Figure 6. Soil residue on tomatoes after cleaning for specified times. Tomatoes cleaned after soil was allowed to dry overnight.

Dried soils with a small amount or with no tomato juice content flaked off leaving small streaks of residue smear. However, when the tomato juice content of the soil was high, a tenacious soil residue remained after drying.

The longer cleaning times required for this soil are shown in Figure 6. Plotting this data on semilog papers gives a curve similar to that obtained for the sum of two independent, first-order processes. This appears to be a common experience of workers studying cleaning of fabrics and hard surfaces (Bourne and Jennings, 1963), and suggests the existence of two species of soil one of which is more closely associated with the soiled surface.

Effect of Detergents and Foams

Figure 7 compares the effect of one hour exposure to water, 0.3% solution of Duponol C, and foam generated from the Duponol C solution on tomatoes smeared with 39% moisture soil. Soil of this moisture content is quite difficult to remove. A two-minute agitated wash does not remove much soil and the effect of soaking in water for one hour before cleaning is neglible. Soaking in the Duponol C solution for one hour removed all the soil without additional cleaning, thus showing the effectiveness of detergents of this type in speeding up the cleaning process. A one-hour exposure to a foam environment removed most of the soil and allowed one-minute wash in an agitated water bath to remove the remaining soil. The foam head above the soiled tomatoes was seven inches, and the tomatoes were supported on a screen which kept them above the small volume of liquid generated by the collapsing foam. The collapsing foam apparently continuously bathes the soiled tomatoes, removing or hydrating most of the soil and thus allowing eash removal of any remaining soil material.

Cleaning With Paraffin Oil

Figure 8 compares the effect of a one-minute exposure in agitated baths of water, paraffin oil, and a paraffin oil-water suspension on the removal of soils of different moisture contents from the surfaces of tomatoes. With a 46% moisture soil (quite watery), all three cleaning media were equally effective, thus confirming the model presented earlier. Water appears to remove soil by slow erosion of the soil surface with complete dispersion of the soil into the water cleaning medium. Paraffin oil tends to roll the water soil away from most of the tomato surface and accumulate it in bead-like mounds due to preferential wetting. The agitated bath removes the mounds of water soil from the surface as discrete drops which fall to the

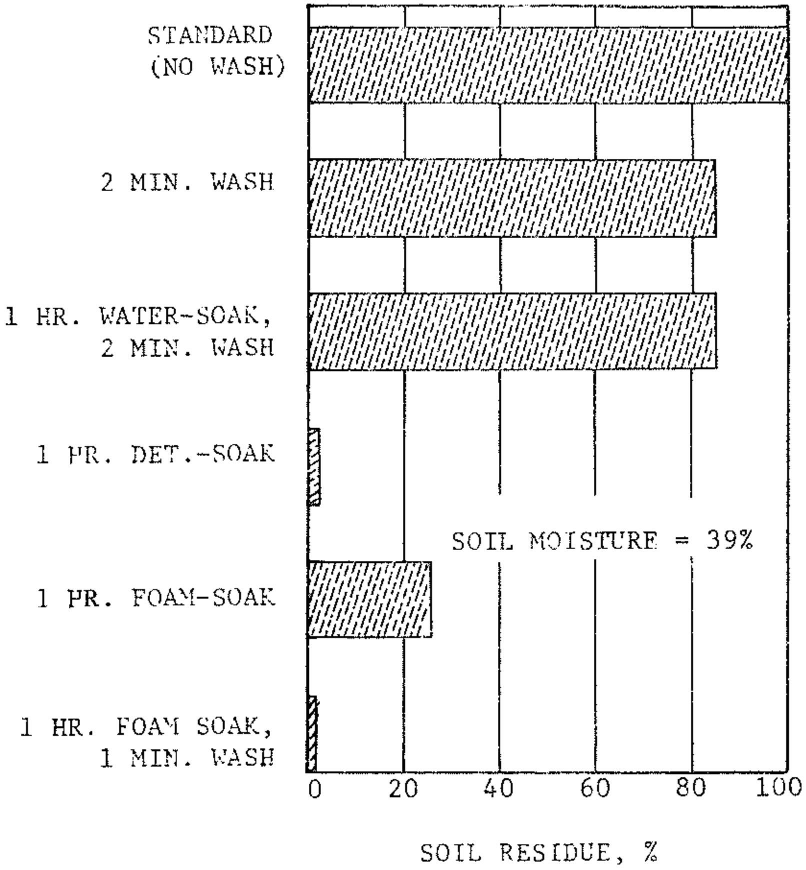

Figure 7. Soil residue on tomatoes after indicated pretreatment and/or wash immediately after soiling.

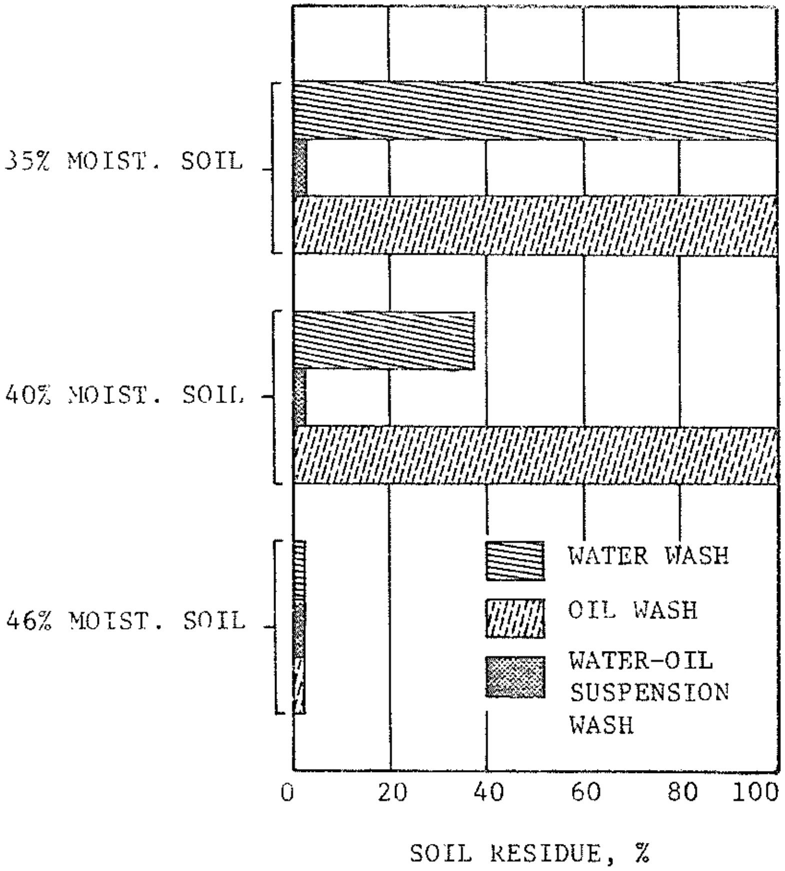

Figure 8. Effectiveness of water, oil, and water-oil suspension in removing soil from tomatoes during one-min agitated bath wash immediately after soiling.

bottom of the bath intact. It was impossible to observe the soil removal mechanism in the oil-water suspension. However, the soil was found to disperse in the water phase. The suspension broke very quickly, leaving the two discrete phases.

With a 40% moisture soil, water was only partially able to remove the soil in one minute. Paraffin oil was completely ineffective due to the soil's increased stickiness and viscosity. The oil was unable to roll up the soil and displace it from the surface. The paraffin oil-water suspension was very effective in achieving complete removal of this soil. This was even more dramatic in comparison with water or oil alone with the 35% moisture soil. The combination of the two soil-removal mechanisms, erosion and displacement, are apparently more effective than either alone. One factor may be the water content of the suspension which probably acts to increase the soil moisture content, thus increasing the oil's ability to preferentially displace the soil. The soil disperses in the water phase, leaving the oil phase completely clear.

Conclusions

Tomato breakage during harvesting, handling, and transport not only reduces over-all harvest quality, but contributes to soil moisture, soil smearing, and soil adherence. Minimum tomato damage is imperative to the delivery of a clean load. The effect of soil moisture on soiling is dramatic. Soil moistures in the range 20-40% yield a soil easy to smear onto a tomato surface and difficult to remove. Soils with moisture contents on either side of this range do not adhere well and are relatively easy to remove. Thus, harvesting with surface soil moisture below 20% would inhibit tomato soiling. The clean tomatoes obtained from a "dry" hand-picking operation illustrate the advantage of dry harvesting. On the other end of the moisture range, provision for a small amount of water on a harvester in the form of spray mists directed on the tomatoes and/or harvester conveyor belts could push soil moisture more than 40%, thus avoiding difficult-to-remove soil. However, this is not practical due to potential microbial growth on the moistened tomato surface. In any case, the objective is to avoid the approximately 20-40% moisture soil range.

Soils containing tomato juice which are allowed to dry are particularly hard to clean.

Use of a detergent promotes soil removal, thus reducing the energy input required from water and the exposure time for cleaning. Leaching from broken fruit should also be reduced. The potential of a foam cleaning medium in combination with mechanical wiping has been described elsewhere (Krochta et al., 1973). The compactness and low water consumption of the process suggests its use either in the processing plant or on the harvester.

Cleaning results with paraffin oil and paraffin oil-water suspensions indicate that liquids other than pure water may be effective cleaning agents for foods. Hydrocarbons may make useful cleaning media for very wet soils or for soils hydrated by a water pretreatment. Oil-water suspensions appear to be effective over a wide range of soil moisture conditions. A suspension containing a small volume of water (large oil-to-water ratio) would be desirable, since a small volume of concentrated aqueous waste for clean-up and recycle could result. Much work remains; nonetheless, the principle and concept have been demonstrated.

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