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An investigation into the effect of surfactants on iron oxide powder suspension formulations for fingermark development

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ABSTRACT

Iron oxide powder suspension (FePS) is a fingermark development technique that can be used on adhesive and non-porous surfaces, the efficacy of which is known to be influenced by the surfactant used in the formulation. Despite previous work optimising surfactants for use in FePS, there is limited understanding of the interactions between surfactants, powders and fingermark residue which aid the successful development of fingermarks. To better understand the effect of surfactant on development quality produced by FePS, this research assessed a wide range of surfactants of different ionic natures and evaluated their ability to develop fingermarks based on the quality of ridge detail, contrast and background development produced. It was found that surfactants play a critical role in the selective deposition of powder on fingermark residue, as formulations made with only water (no surfactant) produced heavy background deposition. The efficacy of each surfactant depended on the quality parameter considered, and the addition of some surfactants hindered fingermark development. Effective surfactants such as T20, KP and TX100 prevented background development and produced well contrasted developed marks. Poor contrast was produced by LN, SP80/T80 and T80 due to indiscriminate powder deposition either across the entire sample or preventing any powder to deposit on the surface, demonstrating the role surfactants play in allowing powder deposition in this technique. The effectiveness of a surfactant in PS was not directly dependent on its ionic nature, and most surfactants were more effective when diluted from stock concentrations. This research has provided a robust base for future work improving fundamental understanding of FePS, which will greatly aid the efficacy of future optimisation efforts.

1. Introduction

Considerable research has been performed to develop and optimise fingermark detection techniques to increase the rate and quality of detected fingermarks [1–5]. Recent research efforts have focussed on a more fundamental understanding of fingermark residues and methods used to detect them to further optimise these techniques [6]. One such detection method currently used operationally is powder suspensions.

Powder suspension (PS) is a fingermark development technique involving a mixture of an aqueous surfactant solution and an insoluble powder. The resulting aqueous product can be applied using a brush to adhesive and non-porous surfaces to develop fingermarks [7–10]. It is a fast, easy, inexpensive technique and the simplicity of the formulation allows for customisation to improve contrast on a range of surfaces [9]. PS has been shown to be effective in difficult conditions such as on adhesive surfaces and aged or wetted marks [9,11–13]. As the capabilities of this technique are further investigated, it is anticipated to have increased operational uses [14]. The fingermark visualisation manual (FVM) currently recommends carbon-based PS for development of fingermarks on adhesive tape, and iron oxide-based PS (FePS) for use on wetted soft plastics [10].

Previous research has been conducted into determining optimal powder types and sizes however investigation into surfactant properties has been less thorough [15–17]. Research has focussed on FePS as carbon and titanium dioxide-based formulations are commercially available as pre-mixed formulations, whereas FePS must be made up in the laboratory before use. This allows for a high degree of customisation, while remaining relevant for operational use. Many PS formulations have been studied and evaluated in an operational setting, however the mechanism by which this technique is able to develop fingermark remains unclear [18]. It has been suggested that powder particles are suspended by aggregates of the surfactant called micelles, which are

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destabilised by some component of fingermark residue allowing the powder to be preferentially deposited on fingermark ridges [8–10].

Surfactants are commonly used as the primary component of cleaning detergents made to disperse insoluble materials and are used in a number of aqueous fingermark development techniques, such as physical developer and small particle reagent [14,19–21]. There are many kinds of surfactants that can be grouped into two main categories: ionic and nonionic. Ionic surfactants may be sub-classified as cationic and anionic surfactants if the head groups are positively or negatively charged, respectively. Ionic surfactants dissociate into their respective ions when dissolved in an aqueous solution. If the head group has no charge, the surfactant is nonionic and will not dissociate in solution [19,21,22]. A fundamental property of surfactants is their ability to form aggregates called micelles, which only form beyond a point known as the critical micelle concentration (CMC). The presence of micelles is critical to the surfactant's ability to carry out its role of dispersing insoluble materials in a solution. The CMC of a surfactant differs based on factors such as ionic nature, temperature, and pH [19,21–25]. For fingermark development, surfactants are used to decrease surface tension and improve the spreading properties of solutions, features which occur when the surfactant concentration is above the CMC. All effective formulations for fingermark development purposes in previous literature have been nonionic or anionic, likely due to their lower CMC and more abundant nature [21].

Surfactant solutions play an important role in the ability of PS formulations to preferentially deposit on fingermark residue, as well as controlling the consistency and shelf life of formulations [14,26,27]. The type of surfactant used in commercial solutions such as Wet Wop™ is not publicly available, however Jones et al. suggest an anionic surfactant is used [15]. For FePS, Triton X-100 surfactant was recommended for use in 2014, however it has recently become restricted in the UK due to its aquatic toxicity [8,16]. Research performed by Downham et al. suggested that Tween 20 be an effective replacement for Triton X-100, and in 2022 this recommendation was implemented in the current FVM [10,16,27]. Both Triton X-100 and Tween 20 are nonionic surfactants. Despite the research performed to optimise surfactants for use in FePS, there has not been a holistic assessment of the effects surfactants have in this technique. This means that our understanding of surfactants in FePS is limited to the specific types/concentrations used in previous investigations, and any new formulations must rigorously tested to be understood and validated for operational use.

The constant changing of recommendations and restrictions of such chemicals highlights the importance of further understanding of the role surfactants play in PS in order to more efficiently optimise them, as well as making informed future recommendations. This research aims to investigate the efficacy of surfactants within FePS formulations and their role in successful fingermark development on non-porous surfaces, to assist in further understanding and improving the capabilities of this fingermark development technique.

2. Materials and methods

A range of FePS formulations were used to develop fingermarks on non-porous surfaces. To observe the effect of different surfactants, a single source and batch of iron oxide powder was used throughout the study to ensure minimal effects from iron oxide powder batch variation. A magnetic iron oxide powder from Fisher Chemicals (CAS 1317–61–9) was used due to its recommendation in the 2014 FVM for use in FePS [8]. The 2022 FVM recommended powder was not utilised in this study as it commenced before the updated manual was published, however the updated formulation suggests that due to the high cost of the recommended powder, the iron oxide powder from Fisher Chemicals could still be used provided initial tests are done to ensure the batch is effective. Previous work has demonstrated inconsistencies within different batches of the iron oxide from Fisher Chemicals which affects the quality of developed fingermarks [16]. Formulations were tested on fingermarks from a range of donors, ethics approval was completed through the University of Technology Sydney (ETH18–2521) and participants were required to consent to the collection of their fingermarks prior to deposition.

2.1. Surfactants

Ten surfactant solutions were chosen based on previous use in PS research or other fingermark development techniques. Two surfactants chosen (CTAB and SP80/T80) had not been previously investigated for fingermark development. Table 1 outlines the types and stock concentrations of surfactants selected.

Triton X-100, Tween 20, Tween 80, dioctyl sodium sulfosuccinate salt (DOSS), Liqui-Nox and ethylene glycol were purchased from Sigma Aldrich. Kodak Photo-Flo 200 was purchased from Kodak Alaris. Span 80 was obtained from TCI chemicals. Cetyltrimethylammonium bromide (CTAB) was obtained from Fluka analytical. N-dodecylamine acetate (n-DDAA) was obtained from MP biomedicals. Sodium dodecyl sulphate (SDS) was obtained from BDH chemicals. Iron oxide powder (lot # 2185036) was purchased from Fisher Scientific.

For each surfactant, a range of concentrations and powder to surfactant ratios were tested. The formulations detailed in Table 1 made up the stock solution for each surfactant. The stock concentration was tested, as well as half and quarter concentrations. For each concentration, ratios of 1:1 and 1:2 w/v (powder (g): surfactant (mL)) were chosen to investigate differences between consistencies of formulations, as these are the ratios recommended in the 2014 and 2022 FVM respectively [8,10]. This is summarised in Table 2. For both ratios, a formulation made with only water and powder was also tested as a control. A total of 62 formulations were investigated in this stage of the study.

2.2. Fingermarks

Each formulation was tested on fingermarks deposited by four donors of varying deposition quality on three non-porous surfaces; glossy white tiles (Johnson Tiles), resealable clear polyethylene bags (J. Burrows) and 3 mm thick clear glass squares (see Table 2). The glass and tile surfaces were cleaned by wiping with acetone and Kimtech wipes, then

Table 1
Surfactant stock solutions investigated in this study. Stock solutions diluted to half and quarter concentrations were also assessed.

Surfactant Code	Stock solution components	CAS Number	Ionic nature
TX100 [10,16]	25 mL Triton X-100 35 mL Ethylene glycol 40 mL Water	9002–93–1 107–21–1	Nonionic
T20 [10,16]	10 mL Tween 20 90 mL Water	9005–64–5	
T80 [28]	22 mL Tween 80 6 mL Ethanol 60 mL Water	9005–65–5 64–17–5	
SP80/T80	5 mL Span 80 5 mL Tween 80 90 mL Water	1338–43–8 9005–65–5	
KP [9,28]	50 mL Kodak Photo-Flo 200 50 mL Water	57–55–6/ 9036–19–5	
DOSS [10,14]	1.5 g Dioctyl sodium sulfosuccinate 100 mL Water	577–11–7	Anionic
SDS [11]	5.8 g Sodium lauryl sulphate 100 mL Water	151–21–3	
LN [29]	25 mL Liqui-Nox 75 mL Water	N/A	
CTAB	7.29 g Hexadecyltrimethylammonium bromide 100 mL Water	57–09–0	Cationic
n-DDAA[8,30]	4.91 g n-dodecylamine acetate 100 mL Water	2016–56–0	

Table 2
Summary of parameters tested for each surfactant.

Ratio powder (g): surfactant (mL)	1:1	1:2	
Substrates	Ceramic	Glass	Plastic
Concentration of surfactant	Stock	Half	Quarter

rinsed with deionised water before being air dried. Plastic samples were used straight from the packaging. For fingermark deposition, donors were asked to wash their hands five minutes before the first deposition and then wait two minutes in between subsequent depositions. Initial investigations into replenishment time of fingermark residue were conducted and it was determined that the times chosen were sufficient to allow for secretion replenishment, while also considering the time constraints of fingermark collection and donor availability. Immediately before each deposition, donors rubbed their fingertips together for homogenisation of fingermark constituents. This methodology resulted in fingermarks which were predominantly eccrine-rich as no sebaceous-loading activities were performed, however this allowed for more controlled consistency of fingermark residue between deposition sessions. As this study focussed on comparing the effect of surfactants on fingermark residue, the chosen methodology aided in reducing variability of development outside of surfactant interaction.

For each substrate, all donors deposited nine fingermarks using their three middle fingers from either hand in a sequence of three depletions (Fig. 1). A total of 6696 fingermarks were collected, and all marks were developed on the same day they were deposited.

2.3. Development

Fingermarks were developed with FePS formulations using the same method, and all formulations were made fresh before each development. A wet powder squirrel hair fingerprint brush from Optimum Technology was used to gently brush the FePS across the substrate. The suspension was left on the substrate for approximately 15 seconds before being rinsed gently with tap water. Different brushes were used for each surfactant and rinsed thoroughly between application of different formulations to prevent any potential contamination between formulations. Developed samples were dried overnight and photographed using a Canon EOS 800D and Canon EF-S 60 mm macro lens. A Rofin Polilight PL500 was used to apply oblique white light for visual enhancement on the plastic samples.

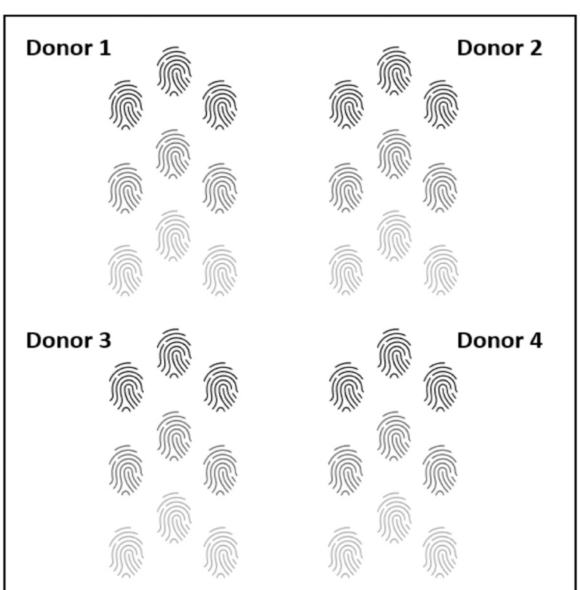


Fig. 1. Illustration of fingermark deposition placement on each substrate.

2.4. Assessment

Each developed fingermark depletion set was graded by one assessor to determine the effects of surfactant type, concentration, and powder to surfactant ratio on fingermark development. The marks were graded based on three different parameters: ridge detail, contrast and background development. These parameters were chosen to provide a more detailed assessment of the suspension's interaction with fingermark residue, as well as with the substrate. Representative grades for each parameter are shown in Tables 3–5. Data was analysed and graphed using Microsoft Excel. For the purpose and ease of data visualisation, scores of 1 or 2 were combined to indicate 'poor quality' scores, and 3 or 4 combined to indicate 'good quality' scores. Optimal development is produced by higher scores, as this represents high quality marks which are more likely to be used for comparison purposes in an operational setting.

3. Results

3.1. Overall results

This study found that all formulations, even those made with only water, were able to develop fingermarks. The addition of a surfactant solution did not always improve development compared to formulations made with only water. The ranked order of surfactant efficacy changed based on the parameter considered (ridge detail, contrast, or background development), suggesting that all surfactants interacted differently with fingermark residue and substrates. The combined results of each grading parameter (ie. all scores of ridge detail, contrast and background development considered together) for formulations made with each surfactant are shown in Fig. 2. To compare the effects of surfactant addition, the combined scores given to marks developed with formulations made with only water (no surfactant) are represented in the background of this graph. This shows that most surfactants improve the development of fingermarks in FePS, except for T80, SP80/T80 and LN. The surfactants which best aid development of parameters assessed with the highest overall scores of 3 and 4 were T20, TX100 and KP (72%, 76% and 78% respectively). T20 was the only surfactant of all those tested that did not produce scores of 0 across any development parameter. The surfactants with the lowest overall scores of 3 and 4 were SP80/T80, T80 and LN (15%, 27% and 36% respectively).

Fig. 2 illustrates an overview of the performance of each surfactant for all concentrations and ratios, however it is important to further analyse these results by separating the scores of each grading criteria. Ridge detail, contrast and background development are all important and interrelated factors that contribute to fingermark quality. To better understand how each parameter is influenced by the type of surfactant, ratio and concentration, further analysis was performed.

To show the relationship between development parameters, surfactants were ranked based on the amount of 'good quality' development (graded 3 or 4) and no development (graded 0). The results of each parameter are shown in Table 6. Some surfactants performed consistently for all criteria such as T20, n-DDAA, KP and SP80/T80. However, others were highly variable depending on which criteria was considered, such as LN and SDS. Interestingly, surfactants of the same ionic nature did not share similarities across any development parameter, suggesting that the type of surfactant does not govern its effectiveness.

3.2. Effect of ratio and concentration

The performance of all surfactants was affected by changes in powder: surfactant ratio and concentration, some to a greater extent than others. Generally, solutions with more dilute surfactants and less powder created thinner suspensions which were more easily brushed onto and washed off the surfaces. However, the reduction of powder and decrease in surfactant concentration did not have a consistent effect on

Table 3
Modified CAST scale used for grading ridge detail present in developed fingermarks [31].

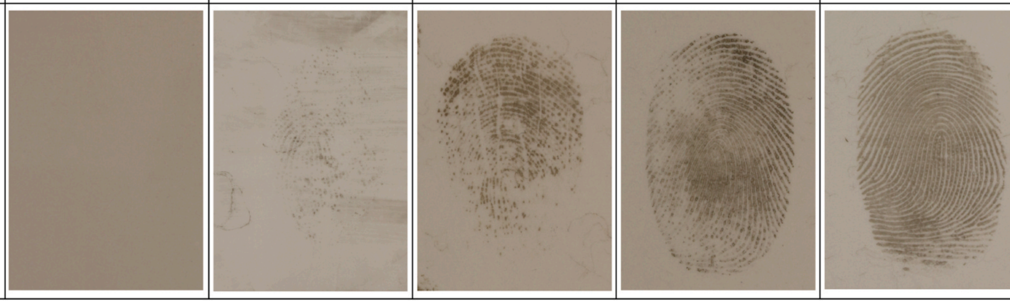
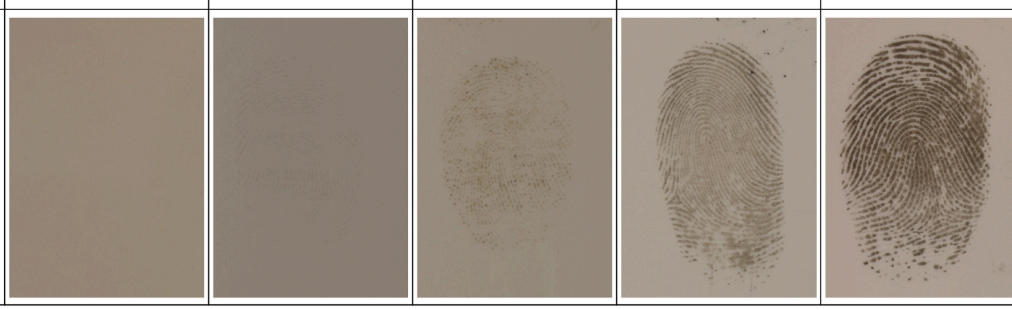
Ridge detail grade	0	1	2	3	4
Criteria	No development	Signs of contact, less than 1/3 continuous ridge detail	Between 1/3 and 2/3 continuous ridge detail	More than 2/3 continuous ridge detail but not quite complete	Full development, whole fingermark, continuous ridges
Example					

Table 4
Scale used for grading contrast present in developed fingermarks [31].

Contrast grade	0	1	2	3	4
Criteria	No contrast between ridges and substrate	Poor contrast between ridges and substrate	Moderate contrast between ridges and substrate	Good contrast between ridges and substrate	Very good contrast between ridges and substrate
Example					

the results of all tested surfactants and was occasionally detrimental to fingermark quality. An example of the variable effect of changing powder to surfactant ratio as well as concentration is shown in Fig. 3. The most effective formulations for each surfactant, determined by the highest amount of 'good' development and lowest amount of no development grades for all quality parameters pooled together, are outlined in Table 7.

Formulations made with only water were effective in developing good ridge detail and contrast, especially on plastic surfaces. However, across all surfaces these formulations also produced the heaviest background development of all tested surfactants, illustrated in the comparison in Fig. 4. Changing the powder to water ratio of these formulations did not have a notable effect on ridge detail and contrast, however the 1:2 ratio increased background development.

3.3. *Effect of surfactant on powder deposition*

To better understand how surfactants may control the volume or size of powder particles being deposited, the scores of contrast was assessed. For surfactants which performed similarly in developing ridge detail, differences in contrast provided further insight into how effective the surfactants were in depositing sufficient powder.

Formulations made with KP, T20 and TX100 produced very similar scores of ridge detail as illustrated in Fig. 5. In the contrast scores however, T20 performed more poorly and received 13% of marks graded 3 or 4 less than TX100 and KP. This was due to very light-coloured marks produced by the stock T20 concentration on all substrates (Fig. 6), despite development of good ridge detail. The 0 grades for ridge detail and contrast produced by KP and TX100 occurred using stock concentrations. When comparing the scores of these surfactants to water (Fig. 5) only TX100 and KP notably improved the contrast of developed marks while very minimal improvement was seen for the ridge detail scores. Despite similar contrast scores for water and T20 formulations, the resulting marks had different amounts of powder deposition onto the fingermark ridges, as illustrated in Fig. 6. Marks produced by water formulations had a high level of powder deposition onto the fingermark ridges but contrast scores were reduced due to background staining, while contrast scores of T20 were reduced by light coloured ridge development. This comparison demonstrates a relationship between contrast and background development, and shows that despite similar

Table 5
Scale used for grading background development around developed fingermarks [32].

Background Development grade	0	1	2	3	4
Criteria	Very heavy background development	Heavy background development	Moderate background development	Light background development	No background development
Example					

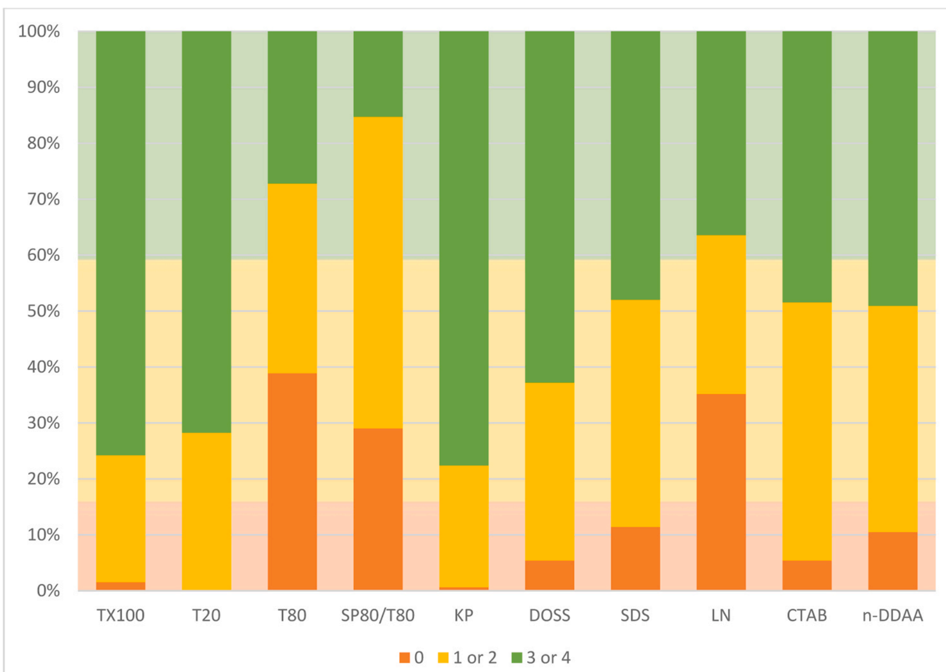


Fig. 2. Total grades received by each surfactant for all formulations and development parameters. Background colour represents scores of formulations made only with water.

scores of ridge detail and background development the addition of T20 does affect how powder is deposited on fingermark ridges using FePS. The addition of all three surfactants had the greatest effect in reducing background development for ideal fingermark development.

Another demonstration of surfactants controlling powder deposition can be observed when comparing the scores produced by T80, LN and SP80/T80. As seen in Fig. 2, the addition of these surfactants hindered the quality of fingermark development overall, however the relationship between the assessed parameters changed for each surfactant. Poor development of ridge detail and low contrast was produced by these surfactants, as illustrated in Fig. 7, however the scores of background development varied. LN produced the least background development of any surfactant, with all marks scoring 3 or 4, however this was due to a lack of powder being deposited anywhere on the surface (Fig. 8) and resulting in poor ridge detail and contrast scores. SP80/T80 and T80 produced moderate to heavy background development, and this prevented any visible ridge detail or contrast resulting in poor scores shown in Fig. 7. The background development produced by T80 was most evident on the plastic substrate (Fig. 8) with 15% of marks on this substrate graded 0 for background development and 65% graded 1 or 2. On ceramic and glass however, notably less background development was present, with no scores of 0 on either substrate and over 90% of marks graded 3 or 4 for both. This demonstrated that volume of powder deposition can also be influenced by substrate.

When formulations made with SP80/T80 were diluted, increased background development was observed across all surface types,

Table 6
Ranking of surfactants for each development parameter (n=11) considering scores for all formulations.

Surfactant	Rank of ridge detail	Rank of contrast	Rank of background development
TX100	1	2	5
T20	3	3	4
T80	11	10	7
SP80/T80	9	8	10
KP	2	1	2
DOSS	4	5	8
SDS	8	9	3
LN	10	11	1
CTAB	5	6	9
n-DDAA	7	7	6
Water	6	4	11

however this also resulted in increased ridge detail and contrast. SP80/T80 also produced some cases of reverse development or voids where fingermark residue was deposited (Fig. 9). Interestingly, these observations were not consistent between donors or substrates, and there was no trend observed in a particular donor or substrate causing the unusual development. The lack of development on the fingermark residue in these cases suggests that there is some component of the residue, which is repelling powder particles suspended by this surfactant, or that the mark is being washed away in the development process.

4. Discussion

This investigation showed that not all surfactants are suitable for use in FePS formulations, and that the efficacy of PS is heavily affected by the type and concentration of surfactant used. It is made clear that the parameters of ridge detail, contrast and background development all contribute to the effectiveness of PS formulations in developing fingermarks.

Overall, KP, TX100 and T20 were the most highly graded surfactants across all development parameters, which is consistent with their effectiveness in current literature. These three surfactants are all nonionic surfactants and were chosen based on their use and effectiveness in previous studies [8,9,13,16,27]. Until 2022, TX100 was the recommended surfactant for use in FePS however it was changed to T20 due to the recent chemical restriction of Triton X-100. Chemical safety and environmental impact are important considerations for fingermark detection techniques, especially for those which are often transported to and used in the field. KP is made up of water and Kodak Photo-Flo, which is a wetting agent used in photographic film development to minimise drying streaks. Kodak Photo-Flo also contains 5–10% Triton X-100 as one of the products along with propylene glycol, meaning its use comes with similar environmental concerns and the production of Kodak Photo-Flo has been discontinued. As T20 is not a toxic product, this research supports Tween 20 as a suitable surfactant for use in fingermark development using FePS [10,13,16,33]. These three surfactants all consistently improved fingermark development compared to formulations made with only water, suggesting that their presence is aiding the mechanism by which FePS is able to develop fingermarks.

While the most effective surfactants were all nonionic, the results of this study show that not all nonionic surfactants are effective. Formulations made with T80 and SP80/T80 produced poor some of the poorest scores across all grading parameters. This highlights that the ionic state may play a minor role in a surfactant's suitability for powder suspension, but it is not the primary factor. SP80/T80 has not been used in published literature for fingermark development, however this mixture has been used in other pharmaceutical and industrial applications [34,35]. T80 however has been used in published PS formulations by Claveria et al. in a new FePS formulation called 'POSME' [28]. The stock T80 concentration used in this investigation is the same as the POSME formulation. In this paper, the authors tested T80, T20 and KP with a range of iron oxide powders and determined that T80 was the most effective surfactant in a PS formulation with Synox Black 6318 iron oxide powder in a 1:1.5 ratio. The Fisher Chemical iron oxide and Sigma nanopowder were not tested. The POSME formulation was used as the second step in a sequential development after dry powder to develop fingermarks on non-porous surfaces and is reported to have improved development. The results of this study are not consistent with the observations of Claveria et al., which may be due to a difference in iron oxide powder used or the presence of residual dry powder in the assessed sequence. However, as the paper focussed on the improvement of fingermarks after dry powder application the results of the surfactant

Table 7
Most effective formulations produced by each surfactant.

Surfactant	Powder: Surfactant ratio	Concentration
TX100	1:1	Half
T20	1:2	Quarter
T80	1:1	Quarter
SP80/T80	1:1	Quarter
KP	1:2	Quarter
DOSS	1:2	Half
SDS	1:1	Quarter
LN	1:2	Stock
CTAB	1:2	Quarter
n-DDAA	1:2	Quarter
Water	1:1	n/a

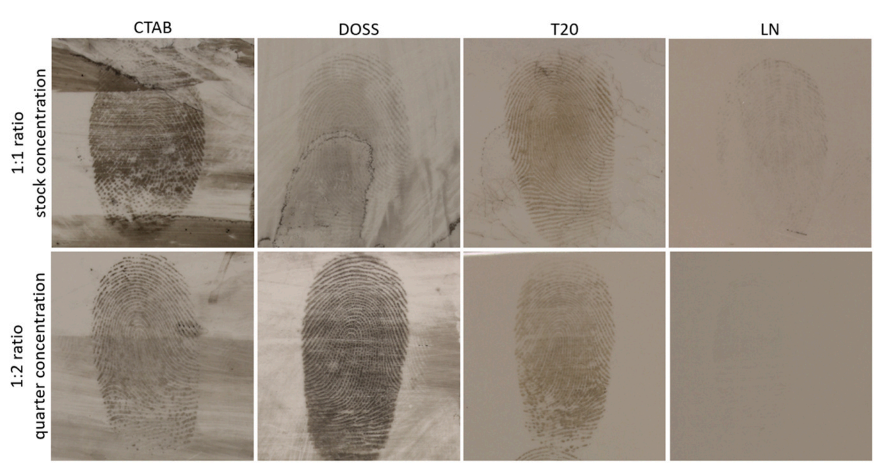


Fig. 3. Comparison of development of one donor on tile substrate produced by surfactants using two different ratios and concentrations. Formulations of 1:1 ratio, stock concentration (top row) and 1:2 ratio, quarter concentration (bottom row).

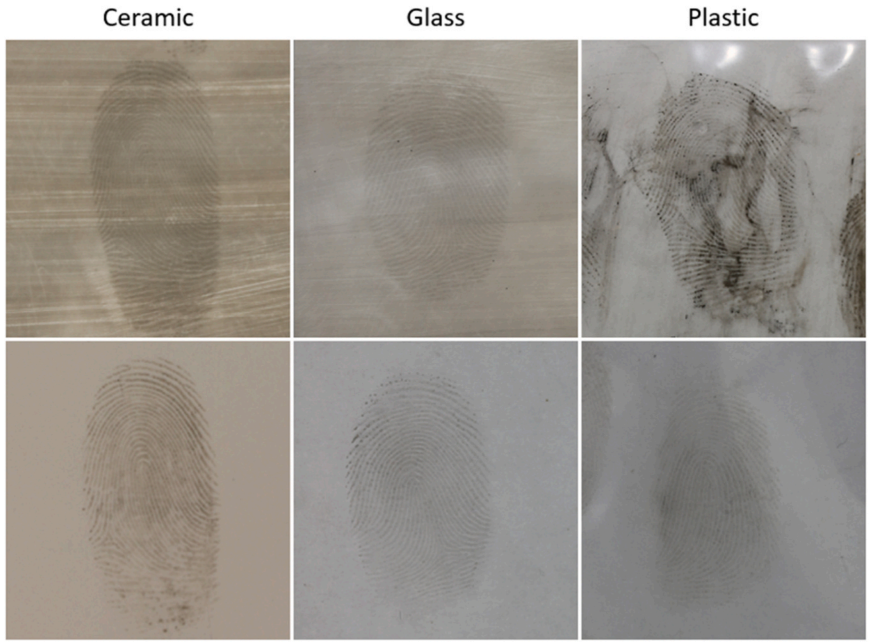


Fig. 4. Comparison of background development on each substrate caused by FePS made with water only (top row) and KP (bottom row).

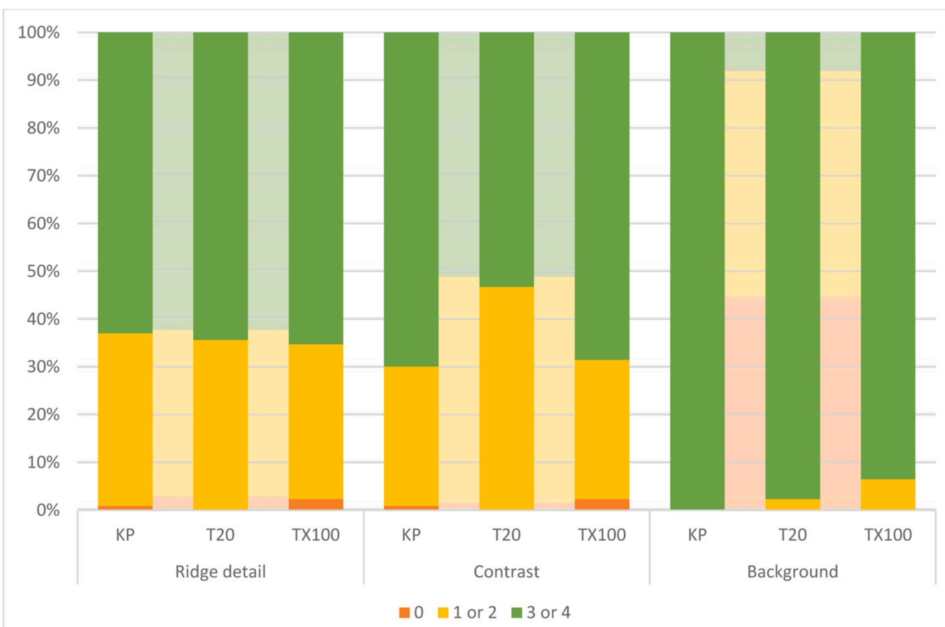


Fig. 5. Combined grades of all KP, T20 and TX100 formulations for each development parameter. Background colour represents scores of formulations made only with water.

comparison were not reported in the published work and can therefore not be readily compared.

The results of this study have shown that the type and amount of surfactant used in FePS does influence the volume of powder deposited on developed marks. Contrast of developed ridges was graded with the aim of indicating any differences between the amount of powder deposited along fingermark ridges with each formulation. This suggests that the role of surfactants in FePS is not only controlling preferential deposition along fingermark ridges, but also the volume or size of powder particles deposited. This may be due to differences in micelles size, shape or their affinity for different components of fingermark residue. A clear example of this variability is in the difference in colour of marks produced with stock concentration T20, TX100 and KP formulations. T20 developed very light, yellow-coloured marks while the others resulted in darker black or grey marks, despite use of the same powder type, batch and weight used in all formulations. This difference in colour has been noted in previous studies investigating both powder and surfactant types in FePS [13,16]. As these studies varied the powders used, it was suggested that differences in colour was caused by powder type rather than surfactant. One study has shown that particles which adhere to fingermark ridges in FePS have a diameter of 0.2–1 µm, even if the powder used is predominantly composed of particles above this range [17]. In other studies, iron oxide nanopowders comprised of particles between 50 and 100 nm have been highly effective and consistent in

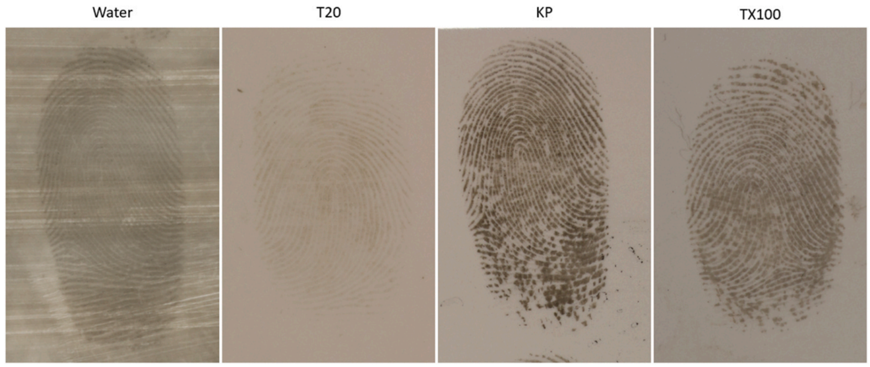


Fig. 6. Comparison of contrast produced by stock concentrations of water, T20, KP and TX100 on ceramic.

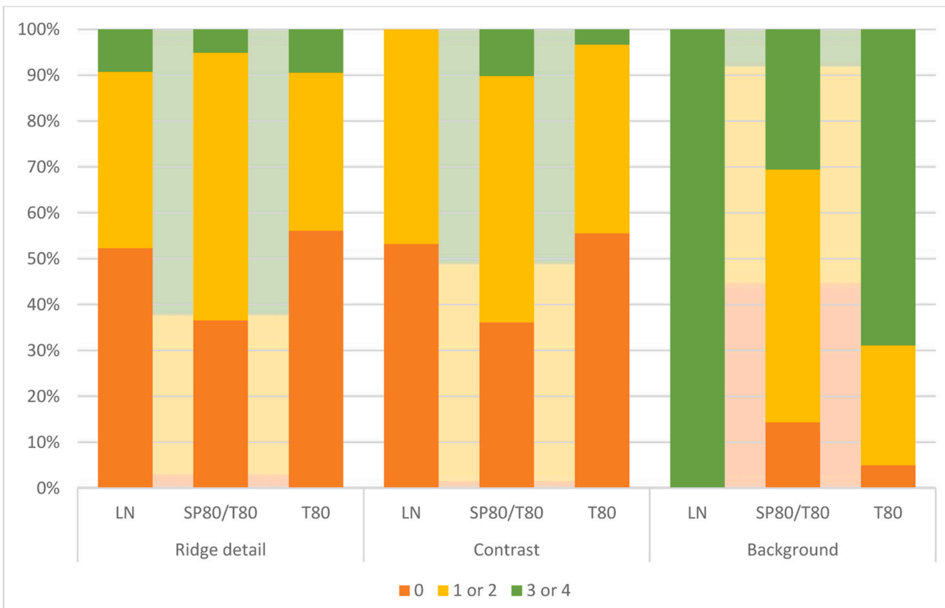


Fig. 7. Comparison of LN, SP80/T80 and T80 for each development parameter.

Fig. 8. Comparison of background development produced by LN (left), SP80/T80 (middle) and T80 (right) on plastic with oblique white light to visualise development.

developing black fingermarks [13,16]. Due to these findings, the 2022 FVM changed its iron oxide powder recommendation from the Fisher Chemical powder used in this study to a nanopowder which seemed to more consistently produce black marks [10,13,16]. The Fisher Chemical powder was utilised as this study was completed before the updated FVM was published. The current FVM suggested that the Fisher

Fig. 9. Reverse development of fingermarks on ceramic using SP80/T80 surfactant at stock (left), half (middle) and quarter (right) concentrations.

Chemical iron oxide may still be used, however users are warned that "batch inconsistencies" may result in poor quality marks which are brown or yellow in colour. As this study was completed using the same batch of Fisher Chemical powder, it is clear that surfactant is also playing a role in the amount and size of powder particles deposited, which in turn influences the colour, contrast and overall quality of developed marks. It is possible that some surfactants are more effective than others at facilitating the interaction between smaller particles and fingermark residue, resulting in higher volume of particles adhering to fingermark ridges. Further studies involving different powders would improve our understanding of this mechanism.

Some surfactants were more affected by changing surfactant concentrations and ratios, while others were able to perform consistently across most formulations. The varying ability of surfactants to perform consistently despite minor formulation changes suggests that there is an optimal range for each surfactant to produce ideal development. This further demonstrates that the interaction involved in the successful development of fingermarks is extremely complex, and is influenced by the intrinsic properties of surfactants. With the current understanding of surfactants and their interaction with fingermark residue, there are a range of possible hypotheses to explain this observation. It is possible that increasing surfactant concentration and reducing powder volume may increase the number of 'free' micelles in a formulation that are not suspending powder particles, and are therefore free to interact with and possible remove the fingermark reside. The shape and structure of surfactant micelles may also play a role in this variation, as the optimal range varies for each surfactant. The sensitivity of surfactants may be influenced by a range of these intrinsic factors, and further work investigating specific parameters is required.

Formulations made only with water were able to produce ridge detail and contrast superior to some surfactants, however it also resulted in the heaviest background development. This suggests that in most formulations, the addition of the surfactant is aiding the selective deposition of powder particles along the fingermark ridges and preventing deposition over the entire substrate surface. The ability of surfactants to deposit powder preferentially on fingermark residue strongly affects its efficacy in PS formulations. This is highlighted by comparing the results of LN, SP80/T80 and T80. The lack of background development caused by LN coupled with poor ridge detail and contrast suggests that the surfactant is preventing powder deposition anywhere on the surface. However, the poor ridge detail and contrast produced by SP80/T80 is coupled with moderate to heavy background development, suggesting that the surfactant is allowing surface-wide deposition which is not concentrated on the fingermark ridges. It also may be that some surfactants are removing the fingermark residue during the application process, leaving nothing for the powder to adhere to. It is important to note that the methodology used during deposition likely resulted in fingermarks from all donors which were predominantly eccrine-rich, as after handwashing donors did not perform any tasks to load sebaceous material or other contaminants. This study has demonstrated that the interaction between surfactants and fingermark residue is more complex than previously thought. However, due to natural donor variation in fingermark residue it is difficult to draw any conclusions about these specific interactions. Without a controlled matrix of known chemical composition our understanding of this relationship remains limited, however advances in research investigating artificial residues may allow future work to better explore this interaction [36–38]. Further studies may be conducted to better understand the influence of different residue fractions and the impact of ageing fingermarks on the performance of different surfactants.

It has been hypothesised that the role of the surfactant is to suspend the powder particles in solution by surrounding them with micelles, similar to the mechanism involved in Small Particle Reagent (SPR) as illustrated in Fig. 10. These micelles are then destabilised by some component of the fingermark residue to allow the selective deposition of powder along the ridges [9,10,14]. There is little evidence to support this theory, however it can be suggested that surfactant micelles have varying ability to allow the optimal suspension and deposition of particles. LN micelles, for example, may not be destabilised sufficiently by the fingermark residue present to allow for powder deposition. However, the SP80/T80 and T80 micelles seem to be releasing the powder regardless of the presence of fingermark residue. Identifying which property of the surfactants is resulting in this difference is crucial to understanding the role of surfactants in producing background development using FePS.

This study has shown that the surfactants tested all interact differently with fingermark residue and substrates, and further indicated the ways in which surfactants are influencing developed fingermark quality that have not yet been investigated. To date, there are no published investigations which aim to improve our fundamental understanding of the relationship between surfactants, fingermark residue and substrates. This research therefore provides a strong foundation and direction for further investigations which may determine what properties are responsible for the variable effectiveness of surfactants in this technique and further optimise FePS formulations to increase our fingermark detection capabilities.

5. Conclusion

This study assessed a range of surfactant types, concentrations and ratios in FePS formulations to determine the effect of the surfactant on fingermark development using this technique. The results showed that there is no trend in surfactants of the same ionic nature in developing ridge detail, improving contrast or reducing background development on non-porous surfaces. The most highly graded surfactant against the assessed parameters was KP due to the high level of ridge detail and contrast produced from all formulations, and lack of background development. The lowest graded surfactant against the assessed

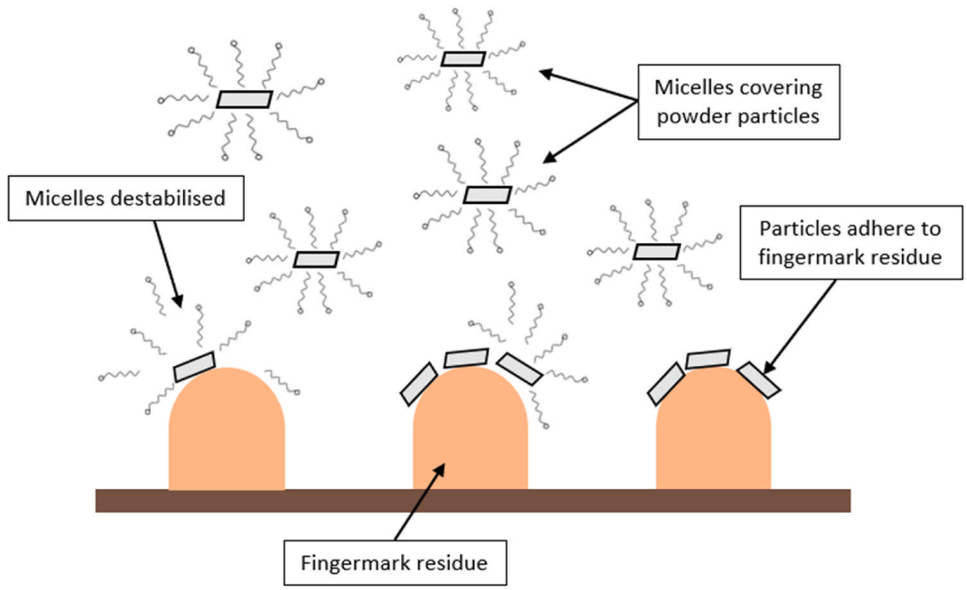


Fig. 10. Proposed mechanism of SPR in which micelles are destabilised by fingermark constituents. Adapted from Bleay et al. [9].

parameters was SP80/T80, which developed very poor ridge detail and contrast, and had a high rate of background development across all substrates. Formulations made with only water were effective in developing fingermarks, however produced heavy background staining which reduced overall quality. This study has demonstrated surfactants play a vital role in preventing background development using FePS and may have a greater influence on the volume of powder deposited on ridges than previously thought. The crucial importance of surfactants in the successful development of fingermarks is outlined by the results of this paper, providing a robust foundation for further investigations.

CRediT authorship contribution statement

Scott Chadwick: Writing – review & editing, Supervision, Project administration, Conceptualization. **Lumikki Clover Ree:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastien Moret:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Mackenzie de la Hunty:** Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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