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# Relevant visualization technologies for latent fingerprints on wet objects and its challenges: a review

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## Abstract

Fingerprint has been one of the powerful evidence in forensic investigation as it is useful for human identification, associating an individual to an item and/or location of interest, as well as reconstructing the crime scenes. Considering that latent fingerprints are commonly found at crime scenes and that it requires the use of fingerprint visualization methods due to its hidden nature, continuous research in developing suitable methods has been reported. However, the underlying physical and/or chemical interactions for certain visualization methods that have successfully visualized wet fingerprints remains unreported. This is probably because previous studies were primarily focused on establishing the fingerprint contrast rather than the comprehension of the physical and chemical aspects behind it. A good understanding on such aspects may prove useful in guiding future improvements, or modifications of existing fingerprint visualization methods. Hence, this review paper focuses on wet latent fingerprints, difficulties in the available wet fingerprint visualization methods, as well as its overview of the challenges and future insights.

**Keywords:** Forensic science, Latent fingerprints, Physical developer, Small particle reagent, Immersed objects, Challenges

## Background

### Fingerprints and its evidential values

Saferstein (2013) stated that the admissibility of fingerprints in the court of law has always been rested on the premise of its (a) individual characteristic, (b) persistency throughout an individual's lifetime, and (c) systematic classifications of general ridge patterns. The first principle stated that every individual, including identical twins, has its own distinctive fingerprints (Wertheim 2011; Champod 2013; Hutchins 2013; Fish et al. 2014; Daluz 2015). Such uniqueness relies profoundly on the identity, number, and relative location of the minutiae (Fig. 1) in point-by-point comparison of known and unknown prints (Saferstein 2013; Houck and Siegel 2015). Owing to its physical attachment to the dermis (Maceo 2011), fingerprints persist throughout an individual's lifetime, provided that there is no deep-seated injury that penetrates the dermal papillae of the skin (Hutchins 2013; Houck and Siegel 2015). Nevertheless, such injury simply offers a new ridge characteristic which may be possibly valuable for identification (Maceo 2011; Saferstein 2013). Although the appearance of the prints may appear "less sharp" as a person ages, which corresponds to the loss of elasticity of the skin, the arrangement of friction ridge skin would remain unchanged (Maceo 2011). Furthermore, fingerprints have general ridge patterns that can be systematically classified into loops, whorls, and arches (Fig. 2) with its relative worldwide population percentages being 60–65%, 30–35%, and about 5%, respectively (Saferstein 2013; Celko 2014; Fish et al. 2014; Houck and Siegel 2015). In addition, these general patterns can be further classified into radial and ulnar loops, plain whorl, central pocket loop, double loop, accidental, as well as plain and tented arches (Saferstein 2013).

Fingerprints can be defined as the impressions of friction ridge skin of fingers that are left on a surface of an object upon contact (Barnes 2011; Saferstein 2013;

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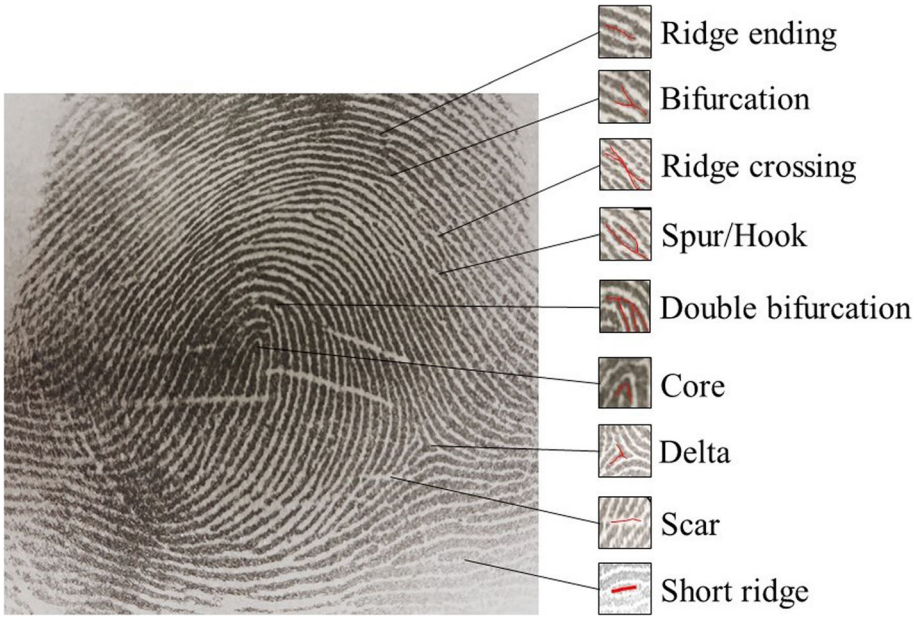



**Fig. 1** Some of the different minutiae of a fingerprint

Houck and Siegel 2015). For forensic applications, fingerprints fall into three different natures viz. latent, patent, and plastic (Saferstein 2013; Daluz 2015; Houck and Siegel 2015; Kobus et al. 2016). Being frequently encountered at crime scenes (Croxton et al. 2010; D'Elia et al. 2015; Lee and Joullié 2015; Kobus et al. 2016), latent fingerprint continues to pose challenges to forensic scientists due to its problematic hidden nature, and hence necessitating the use of optical, physical, and/or chemical visualization methods for comparison and identification purposes (Saferstein 2013; Daluz 2015; Houck and Siegel 2015). Patent fingerprints are readily visible prints upon contact with transferable colored media (e.g., blood and paint), whereas plastic fingerprints refer to the impressions made on soft, malleable objects (e.g., putty and wax) (Yamashita et al. 2011; Saferstein 2013; Daluz 2015; Houck and Siegel 2015), making them relatively easier for forensic analysis, as opposed to that of the latent ones.

### Rationale of this review

The different chemical reactions between the respective visualization methods with that of the available water-soluble (e.g., amino acids) and water -insoluble (e.g,. fatty acids) constituents of fingerprints serve as one of the bases for successful visualization of latent fingerprints (Houck and Siegel 2015; Kasper 2016). Therefore, understanding the chemical interactions/mechanisms as well as advantages and disadvantages of the available


**Fig. 2** The general ridge patterns of a fingerprint

methods for visualizing latent fingerprints on wet objects may prove useful for further improvements and method developments. Unfortunately, chemical interactions/mechanisms for several visualization methods of latent fingerprints on wet objects are scarcely reported in the body of literature. This review paper further accentuates the need for developing suitable greener visualization technologies for environmental sustainability, as well as challenges that may cause difficulty for visualizing latent fingerprints on wet non-porous objects.

### Prevailing knowledge on chemical constituents in fingerprints for enabling visualization

Studies on the chemical constituents of fingerprints have been extensively documented in the body of literature (Ramotowski 2001; Croxton et al. 2006; Drapel et al. 2009; Connatser et al. 2010; Lim et al. 2011; Frick et al. 2015) mainly focusing on the development and/or improvement of the visualizing reagents, dating of fingerprints, and donor profiling (Girod et al. 2012). It has been reported that fingerprints are principally formed by natural secretions of eccrine and sebaceous glands. While eccrine glands secrete mainly water (about 98%) (Ramotowski 2001), organic (e.g., amino acids) (Ramotowski 2001; Croxton et al. 2006; Drapel et al. 2009; Connatser et al. 2010; Lim et al. 2011), and inorganic compounds (e.g., sodium and potassium) (Ramotowski 2001), sebaceous glands secrete mostly fatty acids, squalene, cholesterols (Ramotowski 2001; Hartzell-Baguley et al. 2007; Croxton et al. 2010; Koenig et al. 2011; Lim et al. 2011), and wax esters (Ramotowski 2001; Croxton et al. 2010; Koenig et al. 2011). The presence of exogenous contaminants in fingerprint constituents such as food residues, dust, bacterial spores (Ramotowski 2001), and drugs (Szynkowska et al. 2009; West and Went 2009) were also reported in the literature. The initial constituents of fingerprints tend to vary over time, attributable to factors such as donor characteristics (e.g., age and gender), deposition conditions (e.g., pressure and duration of contact) (Girod et al. 2012; Frick et al. 2015), and nature of the substrate (e.g., porous and non-porous) (Girod et al. 2012).

Additionally, it has been described that the amount of fingerprint constituents varies significantly between samples of the same (intra-variability) and different donors (inter-variability) (Archer et al. 2005; Weyermann et al. 2011), presumably due to reasons such as uneven deposition pressure and contact. However, Archer et al. (2005) also argued that because of the wide variability of fingerprint constituents, predictions of the age of fingerprints within reasonable margins remain limited. Besides, researchers have documented about the notable differences in sebum constituents in children and adult's fingerprints within 4 weeks of observation (Antoine et al. 2010). Similarly, Williams et al. (2011) stated that the number of total residues obtained and the ratio of droplets to particles are noticeably higher in female adult when compared to children of the same gender. However, the authors also pointed out the similarity between the fingerprint deposits of female children with that of adults in certain cases, probably due to the physiological changes associated with the onset of puberty. In a study by Blasdell (2001), the author investigated the longevity of a child's fingerprints with that of adults. He reported that the fingerprints of children disappeared much sooner than that of adults (in as early as the fifth day of the observation), probably because children are known to have considerable amounts of volatile esters in their fingerprint constituents (Williams et al. 2011) which subsequently evaporated at a faster rate than that of adults (Buchanan et al. 1997). In another study by Croxton et al. (2010), the researchers reported higher individual mean of amino acids (particularly asparagine) in females as compared to males. On the contrary, the authors reported lower mean amounts of most fatty acids per fingerprints in females than that of males, although this was reported as statistically insignificant. Ferguson et al. (2012) while studying the direct detection of peptides and small proteins in fingerprint constituents using matrix-assisted laser desorption ionization mass spectrometry profiling with multivariate statistical analysis reported 85% accuracy at distinguishing gender. Considering the varying factors that can affect the quality of fingerprints discussed above, visualizing latent fingerprints for forensic purposes are often challenging. The relevant methods for visualizing wetted latent fingerprints are discussed below.

## Main text

### Developments of physical and chemical fingerprint visualizing methods for wet surface

Over the years, researchers have been consistently exploring new fingerprint visualization methods, and subsequently improving them. Commonly, the selection of visualization methods relies on the nature of surface examined (i.e., porous, semi-porous, non-porous, wet, or dry), available constituents of latent fingerprints (e.g., amino and fatty acids), as well as the order of the method application (Bramble and Brennan 2000; Ramotowski 2012a; Saferstein 2013; Houck and Siegel 2015; Kasper 2016). In view of forensic practical caseworks, latent fingerprints can be visualized using physical and/or chemical methods (Saferstein 2013; Houck and Siegel 2015). In this paper, discussion on the physical method, i.e., powder suspension techniques (viz. small particle reagent (SPR) and general powder suspensions), as well as chemical methods that include iodine fuming, physical

developer (PD), multi-metal deposition (MMD), single metal deposition (SMD), as well as Oil Red O (ORO) will be made. The comparative fingerprint visualization methods are included in Table 1, the details of which are discussed below.

## Physical visualization method: powder suspension techniques

### *Small particle reagent*

SPR (wet powder suspension) was introduced to visualize latent fingerprints on non-porous objects that were accidentally or deliberately wetted (Trapecar 2012; Fish et al. 2014; Houck and Siegel 2015; Kasper 2016; Rohatgi and Kapoor 2016). Researchers concurrently assumed that SPR adheres to the lipid-soluble constituents of fingerprints (Lennard 2007; Daluz 2015; Houck and Siegel 2015; Bumbrah 2016). Such assumption was also supported by Goldstone et al. (2015) when they reported poor performance of black and white SPR in visualizing latent fingerprints exposed to sea spray aerosol, possibly due to the lost sebaceous constituents to such exposure.

Traditionally, SPR is a suspension of fine particles of molybdenum disulphide ($MoS_2$) in a mixture of water and surfactant (Ramotowski 2012a; Daluz 2015; Bumbrah 2016; Kasper 2016). Other than black, SPR comes in two other color variants viz. white and fluorescent. For dark or multi-colored surfaces, the addition of fluorescing agents was suggested by Springer and Bergman (1995). The authors reported that Brilliant Yellow 40 gave better contrast of visualized fingerprints under excitation in the blue range of spectrum, when compared to that of Rhodamine 6G. When Frank and Almog (1993) investigated the best formulation of white SPR, the authors concluded that fine suspensions of zinc carbonate (0.66 g), water (20 mL), tergitol-7 (0.06 g), and dimethyl ether (55 g) provided the best quality of visualized fingerprints on dark surfaces. However, Dhall and Kapoor (2016), while formulating a novel fluorescent white SPR comprising of rose Bengal dye, reported that visualization of latent fingerprints recovered from destructive crime scene simulations using fine suspensions of titanium dioxide ($TiO_2$) prevailed over the other two combinations viz. zinc carbonate and zinc oxide. The authors also established that regardless of the formulations used, the quality of visualized fingerprints decreased with increasing period of exposure to the simulated destructive crime scenes. Similarly, Rohatgi and Kapoor (2016) found that increased in immersion time would subsequently affect the clarity of the visualized fingerprints, irrespective of the types of surface used. The authors reported that novel SPR-basic fuschin dye formulation showed a relatively better performance in visualizing latent fingerprints on non-porous objects immersed in clean water for 45 days, when compared to that of SPR-crystal violet formulation. In addition, Sodhi and Kaur (2012) reported clear, sharp, and detailed quality of visualized fingerprints on non-porous objects after those were immersed in water for up to 36 h. However, the authors did not clarify the type of water used (e.g., tap, pond, or drainage water), and whether the experiment was conducted in an indoor or outdoor setting.

Trapecar (2012) investigated the recovery of fingerprints on transparent foils immersed in stagnant and cold drinking water for up to 168 h using Swedish soot mixture powder, white SPR, and cyanoacrylate fuming. The author reported that among the three visualization methods, white SPR was deemed the best method to visualize wet latent fingerprints. In cases where ninhydrin and cyanoacrylate fuming failed to perform, McDonald et al. (2008) recognized the potential of SPR in visualizing chlorine-exposed latent fingerprints at different levels of humidity (i.e., dry nitrogen, 60% and 100% of ambient humidity). In another study, Kumar et al. (2014) claimed that SPR provided sufficiently clear and identifiable quality of visualized fingerprints on metallic knife immersed in water for up to 20 days, beyond which decreased quality of visualized fingerprints was observed. Kapoor et al. (2015) revealed that with the incorporation of fluorescent rhodamine B dye in SPR formulation, visualized fingerprints on wet non-porous objects immersed in water for 96 h were of clear, sharp, and detailed quality.

However, Jasuja et al. (2008) disclosed that fluorescent SPR formulation based on acridine orange, anthracene, and basic yellow 40 did not revealed positive fluorescent results, although acridine orange did visualize fresh fingerprints. Other than that, the authors also reported successful visualization of latent fingerprints on substrates immersed in water for 96 h using SPR formulation based on rhodamine 6G, rhodamine B, and Cyano blue. Besides offering easy and fast wet visualization, SPR is relatively convenient for any colored surfaces as the formulation can be easily substituted with wide range of fluorescent dyes. However, precautionary measures are greatly advised upon handling SPR due to the toxicities of its chemicals viz. $MoS_2$ and $TiO_2$, as reported in the body of literature (Reid 2002; International Agency for Research on Cancer 2010; National Institute for Occupational Safety and Health 2011; Gao et al. 2015). Unfortunately, despite the continuous developments of SPR formulations, review of literature reveals no specific explanation on the interactions/mechanisms between constituents of fingerprints and compounds of SPR that has enabled the successful visualization of latent fingerprints. Due to such limitation, opportunities for further exploring the theory of such interactions may prove useful.

**Table 1** Comparative fingerprint visualization methods for wet surfaces

| Category | Method | Variants | Possible interactions | Surface (wet) | Application | Specific condition | References |
|---|---|---|---|---|---|---|---|
| Physical | Small particle reagent (SPR) | Black, white and fluorescent | Adheres to the lipid-soluble constituents of fingerprints | Non-porous | Spraying, dipping | Requires rinsing with water | Trapecar 2012; Fish et al. 2014; Houck and Siegel 2015; Kasper 2016; Rohatgi and Kapoor 2016 |
| | General powder suspension (Sticky-side Powder™) | Black and white | Adheres to the water-soluble constituents encapsulated within the non-water soluble constituents | Non-porous or semi-porous surface of sticky side of adhesive tapes | Spraying, dipping and painting | Requires rinsing with water | Burns 1994; Downham et al. 2012; Bandey et al. 2014; Champod et al. 2016; Bleay et al. 2018 |
| Chemical | Iodine fuming | None | Adheres to the lipid-soluble constituents of fingerprints | Non-porous and porous | Fuming | Heated iodine crystals in a closed fume cupboard<br>May be fixed with 1% of starch solution/7,8-benzoflavone | Ramotowski 2012a; Saferstein 2013; Houck and Siegel 2015; Champod et al. 2016; Kasper 2016 |
| | Physical developer | None | Reacts with water-insoluble constituents of fingerprints | Porous | Dipping and immersion | Extremely clean laboratory glassware<br>May require pre-washing with non-chlorinated acids (for paper-based) | Yamashita et al. 2011; Braasch et al. 2013; Fish et al. 2014; Daluz 2015 |
| Chemical | Multi-metal deposition (MMD) | MMD-I and MMD-II | Reacts with the water-insoluble proteins that are trapped within the lipids | Non-porous, semi-porous, and porous | Immersion | Scrupulously clean glassware<br>Restricted working pH (less than pH 3) | Saunders 1989; Schnetz and Margot 2001; Becue et al. 2007; Bécue and Cantú 2012; Becue et al. 2012; Ramotowski 2012b |
| | Single metal deposition (SMD) | None | Reacts with the water-insoluble proteins that are trapped within the lipids | Non-porous, semi-porous, and porous | Immersion | Extended working pH (up to pH 6.7) | Stauffer et al. 2007; Durussel et al. 2009; Becue et al. 2012 |
| | Oil red O (ORO) | None | Generally reacts with lipid-soluble constituents of fingerprints | Semi-porous and porous | Staining | Requires rinsing with water | Salama et al. 2008; Ramotowski 2012b; Frick et al. 2013 |

### *General powder suspensions*

Historically, the development of conventional black powder suspensions (which later commercialized as Sticky-side Powder™) for developing fingerprints on the sticky side of tape was first introduced by Burns (1994). Beneficially, powder suspension techniques work best on sticky-side of the adhesive tapes where common powder methods are futile. As the name implies, this technique is based on suspended powder particles (carbon-, titanium dioxide-, or iron-based) in a mixture of water and diluted detergent (e.g., Kodak Photo-Flo™ or Liquinox™), which is basically similar to that of SPR except for its thicker (paint-like) consistency (Champod et al. 2016; Bleay et al. 2018). This technique has been reported suitable for enhancing fingerprints on wet non- and semi-porous surfaces (Downham et al. 2012; Bandey et al. 2014; Bleay et al. 2018) via spraying, painting, and dipping (Daluz 2015). Because the traditional black powder suspension produced poor background contrast on dark surfaces, Wade (2002) investigated the potential combination of Kodak Photo-Flo with white SPR (titanium dioxide-based powder) where better quality of visualized fingerprints on both sides of black tape was observed than the use of white SPR alone. Similar efficiency of such reagent was also further supported by Williams and Elliott (2005). It has been speculated that the successful visualization of fingerprints using this technique is associated with its interactions with that of the water-soluble constituents encapsulated within the non-water soluble constituents (Bleay et al. 2018). Unlike any other powder-based method, wet powder suspension techniques have been reported to work best on aged latent fingerprints (Bleay et al. 2018). Downham et al. (2017) reported that the concentration of the surfactant in the iron-based reagent plays a major role in determining the clarity of the quality of visualized fingerprints, probably because surfactant helps to control the preferential deposition of suspended powder particles onto the constituents of fingerprints by forming stable micelles (Bleay et al. 2018). For multi-colored surfaces, fluorescent powder suspensions (e.g., rhodamine 6G and basic yellow 40) were introduced. Despite its usefulness in visualizing wet latent fingerprints, the mechanism behind the successful visualization remains a subject of debate.

## Chemical visualization methods: iodine fuming, physical developer, multi and single metal depositions, as well as Oil Red O

Since the choice of chemical methods relies largely on the available constituents of fingerprints as well as the sequence of application (Saferstein 2013; Daluz 2015; Houck and Siegel 2015; Kasper 2016), careful selection of such methods must be made, as one method might preclude the other or reveal more fingerprints than one process alone (Kasper 2016).

### *Iodine fuming*

Because of its application, iodine fuming is generally considered as a traditional chemical method. However, rather than altering the chemical constituents, it merely enhances the appearance of latent fingerprints (Ramotowski 2012c; Kasper 2016). It has been reported that heated iodine crystals would bind to the lipid constituents of fingerprints and subsequently visualizing them (with a brownish hue) (Jasuja et al. 2009; Saferstein 2013; Daluz 2015; Champod et al. 2016; Kasper 2016); however, the chemistry behind its successful visualization remains unreported. Although iodine fuming is relatively simple, fast, and non-destructive, as well as suitable for porous and non-porous surfaces (Champod et al. 2016), the visualized fingerprints have been reported to be transient in nature (Ramotowski 2012c; Saferstein 2013; Houck and Siegel 2015; Champod et al. 2016; Kasper 2016). Due to such drawback, iodine-visualized fingerprints are commonly fixed with chemical fixing agents such as 1% solution of starch in water (Saferstein 2013) and 7,8-benzoflavone (Champod et al. 2016). Recently, Jasuja et al. (2012) formulated and introduced alkaloid brucine as the iodine-fixing reagent. The authors demonstrated successful visualization of latent fingerprints on porous and non-porous surfaces using the formulation of vapor and dipping methods, respectively. Despite many successes in visualizing latent fingerprints, studies reported that iodine vapor is toxic as well as corrosive (Daluz 2015; Champod et al. 2016; Kasper 2016), and therefore, great precaution must be exercised when using iodine fuming method.

### *Physical developer*

The use of physical developer (PD) reagent in visualizing latent fingerprints was dated far back in the early of 1970s (Yamashita et al. 2011). The development of PD for visualizing latent fingerprints on wet-porous surfaces, by targeting the water-insoluble (e.g., lipids) constituents, is undoubtedly useful (Wilson et al. 2007; Ramotowski 2012b; Saferstein 2013; Daluz 2015; Houck and Siegel 2015; Kasper 2016). However, de la Hunty et al. (2015b) recently challenged such classic assumption on the basis that PD still revealed positive results upon the artificial removal of lipid constituents of fingerprints using various organic solvents. In another study by the same authors (de la Hunty et al. 2015a), PD was found to be positively reactive toward the eccrine secretions, thereby postulating that PD may not be exclusively targeting lipids, but may be selective toward eccrine constituents too, or a mixture of both. Nevertheless, the real target constituents of PD remain baffling, and hence, necessitating the need to further explore the chemistry

behind PD. In addition, Saferstein (2013) and Sauzier et al. (2013) stated that PD is especially effective in providing identifiable and good quality of visualized fingerprints on porous objects where other visualization methods might have failed, along with developing aged fingerprints (Yamashita et al. 2011; Braasch et al. 2013; Fish et al. 2014; Daluz 2015). It has been reported that PD is also useful on dry, porous surfaces (Ramotowski 2012b; Saferstein 2013). However, if PD is to be used along with other visualization methods (e.g., ninhydrin), it must be in the last of sequential processing, a concept which is agreed upon by many researchers (Ramotowski 2012b; Saferstein 2013; Daluz 2015; Kasper 2016).

The formulation of PD reagent mainly includes $Ag^{+}$ (from silver nitrate) and $Fe^{2+}$ (from ferrous ammonium sulphate) (reducing agent). Additionally, citric acid and $Fe^{3+}$ (from ferric nitrate) are added into the formulation to suppress the reduction of $Ag^{+}$ to Ag, unless it is prompted by the presence of triggering/nucleating sites (i.e., water-insoluble constituents of fingerprints). However, due to this instability, spontaneous reduction of $Ag^{+}$ to Ag may still occur to form colloidal-sized Ag particles in the solution; the formed silver triggers more chain reduction of silver, thereby increasing background staining. To overcome this and to maintain the stability of the working solution, the addition of cationic and non-ionic surfactants appeared advantageous (Wilson et al. 2007; Ramotowski 2012b). It has been reported that spontaneous formation of colloidal-sized Ag particles obtains its negative charge from citrate ions. Thus, the addition of cationic surfactant (n-dodecylamine acetate) stabilizes the PD formulation by suppressing the negative charge of the formed Ag colloids through the formation of micelle that surrounds the Ag colloids. Thereby, causing a shift into positively charged particles to prevent aggregation with other $Ag^{+}$ (Ramotowski 2012b). In view of stabilizing the developing colloid Ag particles (Aslan and Pérez-Luna 2002) and aiding the dissolution of cationic surfactant (Ramotowski 2012b), the non-ionic surfactant (e.g., Synperonic N or Tween 20) is introduced. In addition, substitution of Tween 20 in PD formulation offers a longer shelf life, as documented by Houlgrave et al. (2011).

Generally, PD formulation is made up of three separate stock solutions viz. surfactants (cationic and non-ionic), silver nitrate, as well as redox solutions (ferric nitrate, ferrous ammonium sulphate, and citric acid) (Yamashita et al. 2011; Daluz 2015; Kasper 2016). Although literature (Ramotowski 2012b) suggested that the three stock solutions are to be added in a manner of ferric nitrate, ferrous ammonium sulphate, citric acid, and lastly the surfactants, Sauzier et al. (2013) disputed this suggestion. The authors reported that the order of addition of the stock solutions did not influence (no significant difference) the performance of each working formulation. However, for standard laboratory practical purposes, the authors suggested that the order of addition was to remain as such. While investigating the modifications of PD formulation, Burow et al. (2003) discovered that with the incorporation of reverse osmosis/deionized (RO/DI) water as a substitution for distilled water in the traditional formulation, the amount of surfactants needed can be subsequently reduced. This is largely because RO/DI water contains relatively less ions than that of distilled water, thus, less amount of surfactant is needed to suppress the negatively charged Ag colloids. Additionally, the authors also revealed that by reducing the concentration of silver nitrate solution from 20 to 16%, relatively comparable and better results were obtained when compared with that of traditional PD formulation.

Despite being advantageous in visualizing aged latent fingerprints, PD is tedious since it requires pre-washing with non-chlorinated acids (e.g., maleic, malic, and dilute nitric acids) to remove the calcium carbonate (which may act as nucleation site) on papers (Burow et al. 2003; Ramotowski 2012b; Kasper 2016). Apparently, this step is necessary as calcium carbonate is a common filler used in the manufacturing of papers (Ramotowski 2012b). While comparable effectiveness in visualizing latent fingerprints on photocopy paper was observed between malic and traditional maleic acids in the acid pre-wash process, the use of malic acid increases background staining that partially obscured the fingerprint ridge (Sauzier et al. 2013), thus complicates the identification process. Aside from being costly (Sodhi and Kaur 2016) and the need to use extremely clean laboratory glassware, the use of PD is somewhat destructive as the method tends to permanently stain the evidence. Also, pre-washing with malic acid may inevitably weaken the fibers of the paper-based forensic evidence, further increasing the possibility of destroying the evidence (Daluz 2015).

#### *Multi metal deposition*

The idea of using colloidal gold nanoparticles in visualizing latent fingerprints on porous, non-porous, dry, and wet surfaces was first presented by Saunders in 1989 in a process known as multi-metal deposition (MMD or recently referred as MMD-I) (Saunders 1989). The two-step process involves the initial deposition of metallic colloidal gold nanoparticles (~ 30 nm) onto the fingerprint residues (specifically amino acids), which subsequently act as nucleating sites for the secondary selective metallic silver deposition (Saunders 1989; Ramotowski 2012b; Champod et al. 2016). It has been reported that gold particles have been widely used in protein detection analyses (Nietzold and Lisdat 2012;

Deng et al. 2016; Lai et al. 2017). The addition of silver-based (modified PD) solution is considered advantageous since the poor contrast of colloidal gold nanoparticles-treated fingerprints (faint pink) would turn visibly dark (Becue et al. 2008; Ramotowski 2012b; Champod et al. 2016).

Despite its universal ability in visualizing latent fingerprints on a wide range of porosity (Saunders 1989; Zhang et al. 2007), this silver-on-gold method is rarely applied in practical caseworks (Becue et al. 2012), attributable to major drawbacks which include the use of expensive reagents and scrupulously clean glassware, laborious procedures (at least 1 h of processing due to the requirement of many immersion baths) (Saunders 1989; Ramotowski 2012b), and the possibility of over-development of prints (Becue et al. 2012; Ramotowski 2012b). In addition, MMD-I also suffers from limited working pH (~ pH 3) (Saunders 1989; Becue et al. 2012); at higher pH, significant decrease in the efficiency of the method was observed (Bécue and Cantú 2012; Becue et al. 2012). Such outcome is observed due to the loss of electrostatic attraction between the positively charged constituents of fingerprints (water-insoluble proteins that are trapped within the lipids) and negatively charged citrate-capped colloidal gold nanoparticles (Schnetz and Margot 2001; Becue et al. 2007; Bécue and Cantú 2012).

Saunders (1989) also mentioned that the post-treatment of visualized fingerprints with zinc (from zinc chloride) seemed to preclude the efficiency of MMD, since the formation of zinc ions subsequently interferes with the formation and stability of the colloidal gold solution (Ramotowski 2012b). Improvement in the operational performance of MMD-I was documented by Schnetz and Margot (2001) when the authors proposed an optimized modification to the conventional MMD-I, known as MMD-II. Apparently, the synthesis of smaller diameter of colloidal gold nanoparticles (~ 14 nm) followed by the use of hydroquinone/silver acetate developer in MMD-II proved to perform significantly better than MMD-I, with less reported background interference (Schnetz and Margot 2001). Despite such improvements, MMD-II still suffered from limited working pH range (pH 2.5–2.8), the need of numerous immersion baths, as well as extremely clean siliconized glassware. Since the numerous immersion baths are laborious and time consuming, Becue et al. (2007) suggested a modification to the MMD-II method. The authors reported that thiolated cyclodextrins functionalized bare gold nanoparticles with the addition of Acid Blue 25 dye produced readily observable dark-blue prints in a single immersion bath. Although the modified method has been reported to have similar efficiency to the MMD-II in visualizing latent fingerprints (dry, wet, fresh, and aged) on various surface porosity, such method only works best at a restricted pH of 2.65 (Becue et al. 2007).

#### *Single metal deposition*

In the quest to find a better alternative of MMD, Stauffer et al. (2007) proposed single metal deposition (SMD) that incorporates the use of gold-on-gold method. Basically, the first part of SMD is similar to that of MMD process (initial deposition of metallic colloidal gold nanoparticles). The difference between the two methods lies in the second part of the process where hydroquinone/silver acetate developer in MMD method is replaced with hydroxylamine/gold chloride as the reducing agent. With SMD, the labor intensiveness of the typical metal deposition method is reduced from six (in MMD) to five immersion baths with the use of one less reagent, hence subsequently reducing the cost (Stauffer et al. 2007). In addition, Durussel et al. (2009) reported a condition (20 min of immersion time, intense 70 rpm stirring speed, 1:1 mol/mol gold/hydroxylamine ratio with $3 \times 10^{-4}$ M of gold concentration) that had resulted in the best SMD optimized parameters for visualizing groomed fingerprints from two donors on a low-density polyethylene transparent film. The authors also mentioned that the common risk of over-development of fingerprint ridges observed in MMD can be circumvented in the SMD method. Despite reporting satisfactory results, authors (Stauffer et al. 2007; Durussel et al. 2009) did not mention the end-color of the visualized SMD-treated fingerprints, if it is comparable or better than that of the MMD method. Moreover, the authors also did not specify the working pH of SMD used. Since pH is an important factor in MMD method, this can be suggestive that the pH working range for this method being narrow. The addition of aspartic acid conjointly with sodium citrate during the synthesis of gold has significantly extended the working pH of SMD (from pH 2 to pH 6.7), hence improving the robustness of the method (Becue et al. 2012). Although the increased quality of visualized fingerprints at low pH is characterized by the increased electrostatic interactions (since aspartic acid has a lower pKa value), the active role of aspartic acid in allowing the detection of fingerprints at an extended working range of pH remains baffling.

#### *Oil Red O*

Having considered the limitations of PD, the development of Oil Red O (ORO) (a pinkish lipophilic stain used in histology) as an alternative was first popularized by Beaudoin (2004). The author revealed that ORO works best in visualizing latent fingerprints, particularly on porous and semi-porous surfaces, although no direct comparisons with PD were made. In another study by Rawji and Beaudoin (2006), the authors revealed the

superiority of ORO reagent over PD in visualizing latent fingerprints, particularly on thermal and standard white papers. In addition, the authors reported that the mean quality of visualized fingerprints on wet papers following the use of both methods (ORO and PD reagents) was statistically insignificant. Guigui and Beaudoin (2007) while investigating the sequential processing of ORO with 1,8-diazafluoren-9-one, ninhydrin and PD suggested that ORO is to be used after the application of amino acid sensitive reagents, but before PD since it permanently stains the surface (Daluz 2015). Frick et al. (2013) also concurred that PD should be used as the last method in the sequential processing.

In an attempt to produce a relatively non-toxic, economical, and simpler ORO reagent, Frick et al. (2012) proposed the use of ORO in propylene glycol. The authors found out that while the development time using the modified ORO reagent was reduced to only 15 min, the contrast and ridge detail of modified ORO-treated fingerprints were comparable to that of traditional ORO formulation with 60 min of development time. While researchers have consistently agreed on the relatively comparable performance of traditional/modified ORO with that of PD in visualizing fresh latent fingerprints, the latter remains as the best-known reagent to visualize aged latent fingerprints on porous surfaces (Salama et al. 2008; Ramotowski 2012b; Frick et al. 2013). Despite a number of advantages ORO reagent has to offer, the real chemical interactions/mechanisms between those of ORO chemicals with that of constituents of latent fingerprints which has enabled the successful visualization of latent fingerprints are yet to be fully understood.

## Latent fingerprints: challenges and future insights

It has to be mentioned here that "criminals often seek a watery repository for weapons and other evidence of wrongdoing" (Becker 2013). Under such circumstance, water-soluble constituents of latent fingerprints such as amino acids, sodium/salt, and proteins would have been washed off by water, leaving only the non-water-soluble (e.g., lipid) constituents (Daluz 2015). Considering the reported amount of sebaceous constituents in natural fingerprints is generally lower than that of eccrine, this could potentially further complicate the visualization process. Furthermore, latent fingerprints on objects immersed in water are vulnerable to several uncontrollable physico-chemical parameters (e.g., pH, turbidity, and biochemical oxygen demand) of the water which may accelerate the degradation of the latent fingerprints.

Generally, the primary goal in forensic fingerprint method development is always focusing on increasing the contrast between fingerprints and its surface. However, the physical/chemical mechanisms/interactions between the chemicals and target constituents of fingerprints which correspond to the successful visualization of latent fingerprints have been scarcely studied. Hence, it is important that such chemical studies to be explored exhaustively so that room for further improvements can be recognized. While fingerprint visualization methods on dry surfaces are widely available, such cannot be said for wet surfaces. Examples of fingerprint visualization methods suggested for dry surfaces include, but not limited to, powder dusting (Sodhi et al. 2003; Garg et al. 2011; Singh et al. 2013; Badiye and Kapoor 2015), cyanoacrylate fuming (Wargacki et al. 2007; Casault et al. 2016, and amino acids sensitive reagents (Hansen and Joullié 2005; D'Elia et al. 2015). Currently, there are only limited well-established visualization methods that are meant for wet surfaces. Among the well-established methods are SPR and PD for non-porous and porous surfaces, respectively. While SPR utilizes suspension of fine particles (e.g., $MoS_2$ and $TiO_2$) in a surfactant (Ramotowski 2012b; Daluz 2015), toxicities arising from the long-term use of such hazardous chemicals have been associated with numerous adverse effects on human (International Agency for Research on Cancer 2010; National Institute for Occupational Safety and Health 2011; Gao et al. 2015; Wang et al. 2016b) and ecology (Reid 2002; Norgate et al. 2007; Wang et al. 2016a). On top of that, the consistent inadequate quality of fingerprints recovered from immersed evidence continues to pose an uphill challenge, presumably due to the duration of immersion (Trapecar 2012; Rohatgi et al. 2015; Rohatgi and Kapoor 2016) as well as different types of water (Rohatgi et al. 2015). Such observation was also supported by Madkour et al. (2017) whereby the authors reported on relatively poor performance of SPR in visualizing latent fingerprints on glass, metal and plastic surfaces, particularly after exposure to sea and lake waters in different aquaria for more than 24 h.

Moreover, visualizing latent fingerprints on textured surfaces such as unplastered concrete walls, natural rocks, and bricks require very special techniques. Taking into consideration the need to visualize latent fingerprints for forensic identification as well as the possible adverse effects that those chemicals may exert on human and ecology, it is therefore becoming imperative to explore a greener and safer alternative in developing visualizing reagents, preferably via biotechnology routes. Recently, Rajan et al. (2018) proposed a green approach of visualizing latent fingermark on various porosity of dry substrates using nanocarbon powder obtained from the by-product of acid digestion of rice husk. However, its efficacy for visualizing latent fingerprints on wet objects is yet to be explored. Currently, review of literature reveals only one study that explored the use of green biotechnological route for visualizing latent fingerprints (Azman et al. 2018) on wet non-porous objects. Despite

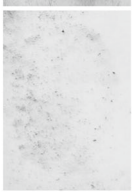
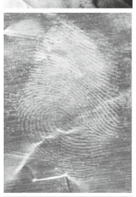
their successful attempt at visualizing latent fingerprints on immersed objects, the method appears tedious and laborious, requiring the use of three different solutions over the span of nine minutes of fingerprint visualization. In addition, the method did not comply with the prevailing International Fingerprint Research Group (IFRG) guidelines, limiting its general acceptance by the forensic fingerprint community. In this context, formulation of a rapid visualization technique using a single optimized nanobio-based reagent with comparable performance as the conventional methods (e.g., SPR and PD) acquires forensic significance.

Although the IFRG Steering Committee has endorsed the guidelines for the assessment of fingermark detection techniques for evaluating a novel or modified method, such guidelines did not outline the protocol for preparing split fingerprints on difficult-to-bisect substrates such as knives, in order to eliminate the intra-donor variability between the two visualization methods (International Fingerprint Research Group 2014). Considering the fact that knife is one of the common weapons used in crime, the protocol for preparing split fingerprints on knives for proposing novel or modified visualization method is therefore deemed necessary. Moreover, because pictorial representation for visualized fingerprints relating to the available grading scales remains unavailable, discrepancies in judgment among the different analysts may prevail, leading to problematic assessments in the evidential values of fingerprint for forensic practical caseworks. Therefore, the suggestive representative photographs of visualized fingerprints on selected substrates against the absolute scale reported by the Centre of Applied Science and Technology (International Fingerprint Research Group 2014) provided here (Table 2) may prove useful.

## Conclusion

The application of fingerprints in criminal investigations has been largely accepted as one of modern, accurate means for establishing human identity. Being commonly

**Table 2** Suggestive representative photographs of visualized fingerprints on selected substrates against the absolute scale reported by the Centre of Applied Science and Technology (International Fingerprint Research Group 2014)

| CAST grading scheme (absolute scale) | | Suggestive visualized fingerprints on selected substrates | | |
|---|---|---|---|---|
| | | A4 white Paper | Aluminium foil | Glass slides |
| 0 | No evidence of a fingermark |  |  |  |
| 1 | Some evidence of a fingermark |  |  |  |
| 2 | Less than 1/3 clear ridge detail |  |  |  |
| 3 | Between 1/3 and 2/3 clear ridge detail |  |  |  |
| 4 | Over 2/3 clear ridge detail |  |  |  |

recovered at scenes of crime, wet latent fingerprints require specific visualization methods with careful regard to its surface as well as the sequential visualization processes; as one method may preclude the other. Although the use of chemical reagents to visualize wet latent fingerprints has been well-reported in the body of literature, continuous usage of these toxic chemicals may cost detrimental effects toward human and ecology. Therefore, in order to minimize such harmful usage while considering the need to visualize latent fingerprints, exploring the green biotechnological studies may be a promising path in fingerprint technology as well as in criminal investigations. Considering the numerous challenges that can be associated with the use of fingerprints for establishing identity, particularly on wetted objects, concerted and continuous efforts to explore new and greener visualization approaches prove necessary.

### Abbreviations

MMD: Multi-metal deposition; $MoS_2$: Molybdenum disulphide; ORO: Oil Red O; PD: Physical developer; SMD: Single metal deposition; SPR: Small particle reagent; $TiO_2$: Titanium dioxide

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### Authors' contributions

ARA drafted the paper. NAM, RAW, and WAA were responsible for critical revision of the paper. MAMH helped in the final revision of the paper. HHH contributed in conceptualization of ideas from practitioner point of view. All the authors read and gave approval for submission.

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Not applicable.

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The authors declare that they have no competing interests.

## Publisher's Note



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