

Adaptive Camouflage Textiles with Thermochromic Colorant and Liquid Crystal for Multidimensional Combat Background, a Technical Approach for Advancement in Defence Protection

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Abstract Adaptive camouflage textiles with color changing and blending into the combat background (CB) and surrounding environments have been a great challenge for the color scientist. Defense professional urgently needs adaptive camouflage textiles for personal protection in extreme weather conditions and multidimensional CB environments. A technical approach of adaptive camouflage textiles can be formulated by using a novel combination of thermochromic colorant and liquid crystal. Absorption of heat can rapidly accelerate the thermal response of thermochromic liquid crystal (TLC) by changing molecular structure with thermo-color-light (TCL) mechanism of absorption and reflection of light at different wavelength. TLC shows chameleon performance of color tone which changes the light reflection of surface color; thus, target objects can be artificially confused by the replacement of chromatic appearance in multidimensional CB environments. TLC can be applied as deceiving mechanism and surface modification of textile substances with combination of dyes/pigment. TLC modified camouflage textiles have possibility of diverse applications in different weather of combat zone for defense actions and different CB environments. A single formulated camouflage textiles may be suited with different CB environments under TLC mechanism. Chameleon type of color tone in cooling and heating conditions of thermochromic changes automatically in both reversible and irreversible way. Therefore, the technical colorant combination has been preached for suitability of adaptation with surrounding CB. TLC treated textiles can be experimented with spectroscopic, microscopic, and photographic illumination. The applications of adaptive camouflage textiles are not only limited to military textiles, but also the principle of technologies have versatile applications for clothing of personal protection including fashionable garments production.

Keywords: *adaptive camouflage textiles, thermochromic liquid crystal (TLC), thermochromic dyes, pitch length, combat background, defence protection*

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1. Introduction

Research and innovation on surveillance technology is being augmented hurriedly under the genuine growth of imaging technology in terms of hyperspectral and digital imaging. Advancement of surveillance technology is being used for both pessimistic and optimistic implementation as per needs of individual groups mainly implemented by special workers in defence. Oppositely researchers and scientists are also demanding to innovate anti-surveillance technology in different fields of engineering and developing chameleon camouflage textiles is one of them. Research and development have

been found in literature review in anti-surveillance technology in terms of camouflage textiles but research in liquid crystal-based chameleon type camouflage textiles is still at the early stage. Chameleon camouflage textiles can change the color for adapting with surrounding environment in different temperature for pessimistic and optimistic implementation as per needs of human being. For example: snow/ice combat background (CB) needs low temperature adaptive camouflage and desert CB demands high temperature background camouflage. Toet [1] reported that army professional needs multi-environment camouflage textiles for single mission of different CB. Neider et al. [2] reported that spectral radiance depends strongly on the illumination incident of the target signature and the atmospheric conditions of CB environment.

2. Background of Technical Approach for Adaptive Coloration Technology

2.1. Natural Existence of Adaptive Camouflage and Theories

Adaptive camouflage has the numerous ways of concealment and disguise in the animal for natural adaptation against surrounding background [152]. In nature, animal has adaptive capability by changing color in different environment. Cuttlefish, octopus, squid, and other cephalopods are the natural examples of adaptive camouflage for the protection of predators [3,4,48,100]. Hanlon et al. highlighted that [153] young cuttlefish use patterning primarily for concealment, such as general colour resemblance, disruptive coloration, obliterative shading, shadow elimination, disguise, and adaptive behaviours. Older cuttlefish also conceal themselves but increasingly use patterns for signalling, both interspecifically (warning or 'deimatic' displays) and intraspecifically (sexual signalling). Nokelainen et al. [111], Thayer et al. [149], Stevens et al. [151] established the concepts of animal concealment from predators. Josef et al. [176] remarked that octopuses have the ability of camouflage creation with surrounding. Stevens et al. [178] investigated that ghost crab (*Ocypodecer atophthalmus*), Singapore can change the color for adaptation with environment. Stuart-Fox et al. [150] remarked the animal color changing pattern and adaptive camouflage in terms of thermoregulation. Rafael C. Duarte [108] studied that some species, rhythms may facilitate thermoregulation and concealment. Merilaita, Lind, investigated that background is an important aspect for concealment and probability of detection by the predator [175]. Rosenholtz [159] commented that shape and orientation of a surface impacts the object recognition, scene perception, and many visual-cognitive tasks. Cuthill et al. [174] studied the bird disruptive and background matching coloration. Silbiger and Munguia [176] experimented that color versus temperature changes of uca pugilator. Therefore, natural existence of adaptive camouflage may motivate the actual development of adaptive camouflage textiles, but the reality of such camouflage textiles still in earlier stage of research and development.

2.2. Basic Phenomenon of Adaptive Camouflage Textiles

Thermochromic colorant may meet the performance requirements of chromatic materials and thermochromic liquid crystal (TLC) acts as deceiving mechanism of adaptive camouflaging under temperature changing against CB [49]. Chromatic materials change the color by the external stimuli like photochromic (light), thermochromic (heat), electrochromic (electricity), solvatochromic (liquid), carsochromic (electron beam). Normally the molecular structure of thermochromic colorant is altered and color changes above room temperature but liquid crystal temperature changes (5-15)^oC and cholesteric type liquid crystal is more suitable for thermochromism, and the pitch of the helical arrangement is responsible for temperature

and reflection in wavelength [85]. Sudhakar and Gobi N [130] proposed chameleon textiles in terms of pH changes, electric or magnetic field effects, mechanochromism, bond breaking/making, oxidation state changes. Polymer binder/resin and pigment for control of gloss, heavy metal pigment, lead, chromium, iron oxide, silica, polyurethane are the materials for camouflage textiles development [88]. Still now, thermochromic materials have limited application in camouflage textiles. Most thermochromic materials are organic having short lifetime and limited range of temperature in combination with liquid crystal. There is need of research for developing wide range of temperature and lifetime properties of thermochromic materials [87,91]. Sudhakar and N. Gobi [88] supported the opinion of Alvenmaa [87] that chromophore with polymeric materials may enhance the stable field of color change process. Adaptive camouflage [43] was proposed by color changing leuco dyes and advised for coupling color changing ability with high stimuli responsive study. Scott [5] claimed that CB environments (temperature, weather, etc.) are the prime question for augmentation of camouflage textiles in terms of adaptation. Joshi [6] also supported for making the chameleon type camouflage fabric by the implementation of light reflection engineering [7]. Heating mechanism influences the thermochromic system for temperature responsive camouflaging [7,8,9,20]. Conner [32] patented a camouflage textile with a material capable of different chromic states at different ambient light levels. The patent also observed the color changes of heat sensitive dyes in terms of both controllable (heat) and uncontrollable temperature (sunlight). Karpagam [62] experimented chemelyon type printing on cotton fabric with thermochromic colorant. CIE L*, a*, b* were measured before and after heating with spectrophotometer. Out of textile engineering, researchers [50] in mechanical system developed adaptive camouflage devices capable of producing black and white patterns for matching with its surrounding. Tianzhi et al. [134] investigated electrical field-based color changing mechanism with invisible sensors. Ying Liet al. [135] developed device for adaptive camouflage with background temperature. US army institute of environmental medicine (USAIEM) experimented the effect of temperature and wind chill on human body such as hot (32^oC), pleasant (28^oC), cool (22^oC), very cool (16^oC), cold (10^oC), very cold (5^oC), bitterly cold (0^oC), fresh freezes (-5^oC), exposed area of fresh freezes within one min (-24^oC) [81]. Temperature mechanism can be used for adaptive camouflage garments in desert (high temperature) camouflage, snow/iceland (low temperature) camouflage, common camouflage textiles in different season, and additionally for fashion textiles. This technology of adaptive camouflage textiles is not limited for garments implementation only, it has versatile applications in defense.

2.3. Selection of Textile Materials versus Thermal Conductivity for Adaptive Camouflage Formulation

Ajeeb [44] suggested higher heat transfer of wool and polyester than cotton. Hearle [80] noted the thermal conductivity of different textile fibre when packing density 0.5m/cc. Cotton (71), wool (54), silk (50), PVC

(160), cellulose acetate (230), nylon (250), polyester (140), polyethylene (340), polypropylene (120). Jassim and et al. [113] mentioned that thermal conductivity in (k)W/(m. K) of materials like acetone (0.16), acrylic (0.2) air, atmosphere (gas) (0.024), alcohol (0.17), carbon (1.7), cellulose, cotton, wood pulp and regenerated (0.23), cellulose acetate, molded, sheet (0.17-0.33), cellulose nitrate, celluloid (0.12-0.21), cotton (0.04), polyester (0.05), polypropylene (0.1- 0.22). Thermal conductivity of textile materials should be selected accurately for temperature responsive coloration of protection textiles.

2.4. Applications of Thermochromic Colorants for Principle of Thermochromism

Diverse applications [11-21,38] of thermochromic colorant has been investigated and successfully applied for commercialization like kitchen aprone and hand gloves, laboratory aprone, safety shoes, medical textiles, flexible display for clothing, transportation of sensitive goods, garments to detect disease and physiological conditions of the wearers, firefighting garments for the protection of extreme temperature, sports wears and building paints.

2.5. Applications of Liquid Crystal for Principle of Thermochromism

Liquid crystal and thermochromic colorants have versatile applications for the principle of thermochromism.

Hallcrest mentioned a brief applications of liquid crystal: a) general temperature indication/digital thermometers: room/household, refrigerator/freezer, infant bath/bottle, aquarium, hot/cold warning indicators b) battery testers and other voltage measuring devices c) temperature indicators for medical applications: forehead thermometers/fever

indicators, hypothermia warning indicators, drug testing; temperature indicating labels for urine specimen authentication d) medical thermography: sub-cutaneous cancer detection, diagnosis of vascular diseases, placenta location, pharmacological tests, skin grafting and vein location, veterinary applications, chiropractic applications e) radiation detection: infrared, microwave, ultraviolet, ultrasonic, electromagnetic f) aesthetic: advertising and promotions, decoration, jewelry, badges, fabrics, clothing and other novelties g) ingredients in cosmetic formulations h) non-destructive testing/thermal mapping: surface and sub-surface flaw detection in metals, welded metals, bonded and other composite structures, fault/short location in electric components and electronic circuits i) aerospace and engineering research: heat transfer studies, flow visualization in fluids and on solid surfaces in airflows j) gas/liquid level indicators k) miscellaneous: chemical and gas detectors, pressure sensors, information displays. Novel applications for liquid crystal are continually under advancement [94]. Application of thermochromism of liquid crystal is not a new approach of thermal engineering. The application of liquid crystal for camouflaging on textiles substances is an innovative approach.

2.6. Principle of Thermochromic Colorant for Color Changing

Thermochromism opined by Andy Town [49], Aitken and et al. reported [155], Eds H.R Mattila [86], J.E Gilligan [28] mentioned and summarized the thermochromic principle in Figure 1. A (green), B (red), C (yellow) are three schematic phases of colorant in three possible temperature ranges. Phase transition occurs under multi-phase heating mechanism in terms of geometrical and molecular structures.

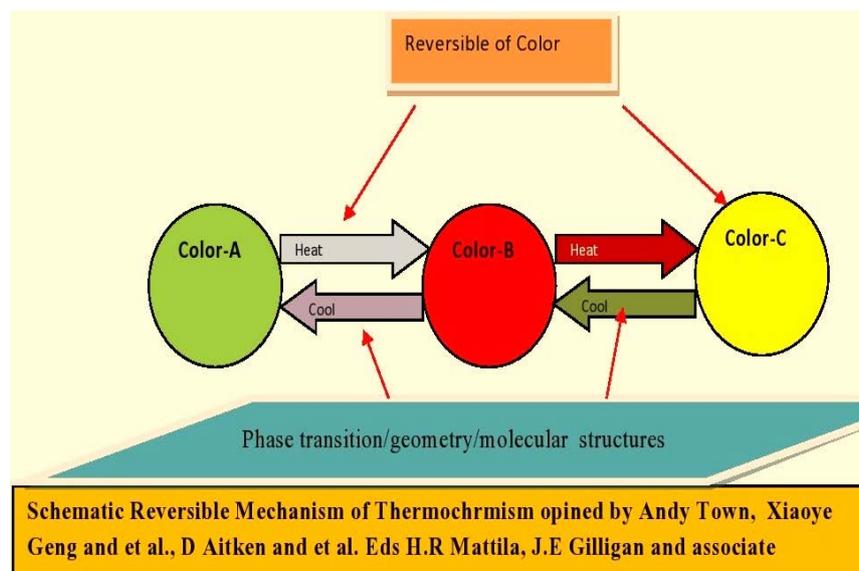


Figure 1. Typical mechanism of thermochromism of thermochromic materials

Thermochromic materials [86,118-121,123,124,127,128] and color changing principle [129] have been used thermal technology but limited for adaptive camouflaging on textile substances [86,118-121,123,124,127,128]. Organic compound shows the variation in crystal structure,

stereoisomer, and molecular rearrangements. Liquid crystal shows different color at different temperature due to variation of reflection in wavelength from low temperature crystalline phase to high temperature isotropic liquid phase. Molecular rearrangement can create new

chromophore for changing color like acid base, keto-enol. Inorganic thermochromism has found drawback in textile application that color often changes at high temperature [86]. Fujita et al. [156] claimed that thermochromic microencapsulated pigment shows a color change temperature regulator. In the same way, Aitken et al. reported [155] that phase transition, geometry and molecular structures influence the thermochromic system. Henry [164] Conner patented coating materials to produce color changes in the camouflaging pattern include light and/or heat sensitive dyes and/or inks. Ramlow et al. [45] recommended that there is still too much to be explored and discovered in the field of chromic textiles [46]. Cheng et al. [53] supported that thermochromic materials are memory functions to the temperature. Thermochromic materials can be used for anti-counterfeiting technology. Geng et al. [54] microencapsulated crystal violet lactone as thermochromic colorant and observed reversible thermochromic properties, improved thermochromism was also investigated when silver nano particle added for modification. In this investigation, microencapsulation was studied by microscopic analysis. Shibahashiet and et. al. [157] opined and patented that the electron donating organic compound for microencapsulated thermochromism. Wilusz [85] reported that Nanta from Toray Industries reported temperature sensitive fabric in 1988 with trade name SWAY by microencapsulation and resin coating. The microcapsule was made of glass and dye chromophore agent was electron acceptor and color neutralizer were alcohol showed color and decolor in terms of environment temperature. Phillips developed fabric changing color from white to blue with ultraviolet (UV) irradiation at 350-400 nm. Ladendal [22] investigated thermochromism of thermochromic leuco dyes and proposed an outcome of color changing with uncontrollable parameter (sun) in print design process. Bourque [23] also studied temperature dependent color changes and experimented the tendency of thermochromism when color density increases with the increasing temperature. Llyod [31] and Rao [24] are also supported thermochromism who developed TLC [25] coated fabric for biomedical application by using leuco dyes for extended temperature range. Vikovaet al. [27] suggested the research scope of light fastness for color changeable thermochromic ink and thermochromic pigment [29]. Borque and researcher team [193] experimented that alkyl chain lengths were poorly matched, the dye-developer interaction dominated in the solid state, and melt-lightened thermochromism was observed. Jin and other researchers [60] experimented a heat stimulated luminous fibre at 30°C-20°C temperature by using heat sensitive pigment TF-G through wet spinning method. Heat stimulation was verified in naked eye by the researchers. Jinet al. [61] investigated a thermosensitive luminous fibre by thermochromic pigment. Researchers observed a rose red at room temperature and fibre sample showed colorless with blue light emission. In this study researchers claimed that phosphorescence of color is responsible for thermochromism. Potucket al. [64] experimented physiological changes of skin temperature range between 33°C and 38°C with artificial microencapsulated leuco dyes named as thermochromic pigment and applied on nylon & spandex blended fabric. Thermochromism

behaviours also studied by Martins [63] at 10°C-60°C. Jassim et al. [113] found that thermochromism showed different colors like orange 30°C, light orange 32°C, light pink 36°C, colorless 41°C. Kulčar and his researchers group [112] proved that the stability of decolorized state was examined at cooling for 10 hours. Ramigand et al. tested [65] thermochromism by reflectance spectra and calorimetry data. Thus, smaller particle tends to create bluer shade and larger particle tends to create redder shade. Z. Ahmed et al. [52] reported that printed thermochromic ink on polyester and cotton blended fabric changes color from black to green in 10.8 s using 1.46 W DC power at 30°C temperature. Researchers recommended that the technology can be extended by choosing right formulation for specific purpose of thermochromism. Dean et al. [154] discovered that FriXion erasable pens contain thermochromic inks that have colored low temperature forms and colorless high-temperature forms. Thermochromic coloration [40,41,42,78] is not a new concept but thermal responsive and adaptive camouflage is a new approach. Kulcuret al. [95] confirmed the reversibility of color change for leucodye-based TC ink. In 2019, thermochromic microcapsule by cationic dye was studied by Ma [68]. Ahmed and his team at IIT, Delhi, India [2,26] experimented the thermochromic colorant on cotton fabric [10] and fabric shade was changed in term of heat. Bristetet al. [70] patented that thermochromic materials produces a visual change of the visible (Vis) surface when an activation temperature of thermochromic materials is reached. Wan Zhang [71] examined the thermochromism performance on polyester fabric at 20°C, 45°C, 80°C with thermochromic leuco dye loaded silica nano capsule. The color reversely changed from dark blue (K/S =12) to light blue (K/S = 2) at 610 nm for more than 50 times. Zhang et al. [72] experimented temperature responsive thermochromic textiles between 5°C and 35°C. Jakovljevic and researcher team [74] studied thermochromism based on leuco dyes and liquid crystal. Choudhury et al. [75] remarked that ultraviolet temperature, p^H is the responsible for color changing of thermochromic colorant. Basnec and his researcher team [101] opined that temperature-dependent colour of thermochromic (TC) materials originates in phase transitions and changes in the geometry of the material when thermochromic composites were prepared using crystal violet lactone (CVL) dye, benzyl 4-hydroxybenzoate (B₄HB) developer and 1-dodecanol (DD) solvent and strongly suggested future study. Thermochromism exhibits with temperature versus color change [103]. Mary et al. [102] stated that temperature decreasing and wavelength increasing like 400 nm, 500 nm, 600 nm, 700 nm, and color change accordingly. Mary et al. [102] focused that neither thermochromic liquid crystals nor thermochromic organic dye mixtures can be applied directly for use in coloration: both require microencapsulation. Schubert et al. [114] focused and supported antireflection coating of four-layer (TiO₂/SiO₂)/nanoporous SiO₂ for the broadband and directional reflection. HULSEY and his team [117] designed temperature versus color change with leuco dye and the product was sold by color change corporation streamwood. Panak et al. [108] experimented CIE lab [126] thermochromism with crystal violet lactone as a colour former, bisphenol A as a developer and tetradecanol as a

co-solvent and researchers suggested thermochromic system based on color change. Bašněc et al. [109] also used lucodye-based composite for thermochromism. Vikova [116] proceeded kinetic model verification on color changeable textile sensor by the process of dyeing and printing. Serenet al. [73] analyzed thermochromism of thermochromic pigment on leather finishing at 15°C and 31°C. The color measurement was studied by spectrophotometer. Candas et al. [66] investigated thermochromism in leather finishing by UV absorber and cross linker. The evidence was supported by spectrophotometer and ageing test. Heet al. [59] observed bisphenol A risk for thermochromic textile product and tested by high performance liquid chromatography (HPLC) method for bisphenol identification.

2.7. Principle of Liquid Crystal for Thermochromism

Dave and Patel [140] mentioned that molecular diameter decreases when temperature raises under the investigations on 4-n Alkoxybiphenyl-4 Carboxylic acids and its 3-substituted derivatives. White [141] reviewed that the use of cholesteric liquid crystals (CLCs) as color changing optical materials. Liquid crystal has phase transition nature [96, 122]. Thermochromic liquid crystals have numerous applications [94] for color changing but the implementation in adaptive camouflaging have not been explored. Ian sage [96, 122] reported the nature of phase transition of liquid crystal technology. Qi Hong [84] investigated cholesteric liquid crystal and suggested that the number of pitches required for the stimulation of reflection. Yu Guan and other researchers [55] used cholesteric liquid crystal 3-30 μm microcapsules as thermochromic materials with electrospinning method and the structure of microencapsulation was determined by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images, core size was studied by TG. This study investigated the thermochromic property from red to blue chromatic hue. Gilligan et al. [28] are critically proposed temperature versus color change properties [33] of cholesteric liquid crystal for reversible, controllable, and reproducible. Aguirre [39] illuminated the reversible color changing property of colloidal photonic crystal. Nadia et al. [197] studied thermochromic liquid crystal for heat transfer. Choudhury et al. [51] commented that temperature can influence the reflection of light by liquid crystal due to having the structure of helices. Therefore, the wavelength of reflected light is altered causing progressive change in color spectrum. Seeboth and Lotzsch [76] mentioned in their book that liquid crystal can flow like fluid. The length of helical pitch depends on the molecular structure and concentration of the chiral compound, phase type and its temperature. Therefore, pitch length influences the thermochromic properties. Choudhury et al. [51] remarked that the liquid crystal materials can be microencapsulated and microcapsules can be used like pigment on the fabric surface with resin binder. Christie et al. [77] experimented thermochromic print based microencapsulated liquid crystal. The effect is most suitable over a black background. Treated nylon and lycra blended fabric was analyzed in terms of wavelength of reflected light, $L^* a^*$

b^* values, lightness, chroma and hue. Christie et al. [91] also remarked that leuco dye and liquid crystal for temperature sensitive environment using thermochromic color change by careful formulation with proposed technology of microencapsulation. Maclaren et al. [83] used crystal violet lactone dyes for reversible thermochromic system. Similarly, Panak and other researchers [93] supported the color change mechanism with CIE lab [42] by demonstrating thermochromic composite in formulation with crystal violate lactone as a color, bisphenol A as developer and tetradecanol as co-solvent.

2.8. Nano Materials for Thermochromism

Smith et al. [35] patented the material coloration using particle scattering and Hemant Kumar et al. [30] reported the feasibility of anti-reflective coating for thermochromism. Kumar et al. [37] studied the thermochromism with vanadium pentoxide coating and suggested the possibility of chromium for thermochromism. Yan and other researchers [98] investigated by x-ray diffraction (XRD) that the degree of crystallization of colored luminous fibre was decreased inorganic pigments when inorganic pigment and luminous materials were used. Xiao et al. [132] opined that the possibility of adaptive infrared camouflage which consists of a vanadium dioxide (VO_2) layer, with a negative differential thermal emissivity, coated on a graphene/carbon nanotube (CNT) thin film. Plan et.al [99] remarked high refractive index of grapheme oxide. Zhu [133] studied for high temperature thermal management in infrared camouflage by combining a silica aerogel for thermal insulation.

2.9. PCM for Thermochromism

Krishna et al. [97] studied that PCM dispersed with different types of nano particle for high thermal storage in terms of microencapsulation and researcher recommended the microencapsulation technique for high thermal storage with nano-PCM. Qu et al. [58] reported that camouflage technique has not adequately explored the ability to continuously camouflage objects either temperature variations or wide observation angle. Researchers developed a thermal camouflage device by PCM $\text{Ge}_2\text{Sb}_2\text{Te}_5$ in 30°C to 50°C and 0° to 60° angle. Wu [67] was studied simultaneous process of color changing and heat changing behavior after 100-time heating and cooling cycle by using spiro lactone color former, phenolic hydroxyl compound as color developer, 1-hexadecanol as PCM and the microencapsulation was achieved by gelatin containing vinyl group and gum arabic to form glutaraldehyde for making stability and encapsulation. Sari et al. [79] experimented with emulsion polymerization method for solid-liquid microencapsulated phase change material (PCM). The chemical and thermal characterization was done by SEM, differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) where the DSC showed energy storage capacity and the TGA confirmed the thermal stability of microencapsulated PCM. The microencapsulated n-heptdecane with polymethylacrylate confirmed 5000 thermal cycles. Burkinshaw et al. [82] experimented with p^H sensitive spiro lactone derived

functional dyes and phase changes occurred during heating and cooling in terms of thermochromic effect. Wbendkowska [90] studied that PCM has latent heat storage capability for thermal application.

3. Materials, Methods, and Experimental Design for Adaptive Camouflage Textiles

Materials, methods, analysis, and observations need a technical combination for adaptive camouflaging on textile substances against multidimensional background environments. The materials, methods, analysis, and observations are not established for adaptive camouflage textiles. Table 1 denotes the selection of suitable textile materials for thermochromism and adaptive camouflage textiles. Common textile materials have been mentioned by defense professional. Table 2 has been listed with thermochromic colorant for chromatic appearance with background environments; and TLC for deceiving

mechanism (Figure 3) at different temperature. Table 3 demonstrates the method of textile treatment for thermochromism as camouflage coloration. Table 4 exhibits the assessment method of thermochromism, and analysis of textile treated samples. Table 5 has been mentioned with color changing parameters for background color matching at different temperature/weather conditions/background environments.

3.1. Textile Materials for Thermochromism

Table 1. Textile materials for thermochromism

References	Textile Materials
Potucket et al. [64]	Nylon & spandex blended fabric.
Ahmed et al. [52]	Polyester and cotton blended fabric
Ahmed et al. [26,190]	Cotton fabric
Zhang [71]	Polyester fabric
Wu et al. [69]	Cotton & polyester blended fabric
Christie et al. [77]	Nylon and lycra blended fabric

3.2. Materials for Thermochromism

Table 2. Materials for thermochromism

References	Materials
Geng et al. [54]	Crystal violet lactone
Ladendal [22]	Thermochromic leuco dyes
Rao [24]	TLC, leuco dyes
Salek et al. [25,55]	TLC, Zn ₃ (PO ₃) ₂ S (irreversible)
Odwa et al. [57]	Polydiacetylene (reversible color blue), 10, 12 pentacoadiynic acid group of urea
Jin and other researchers [60]	Pigment TF-G
Jin et al. [61]	Pigment
Potuck et al. [64]	Leuco dyes
Kulcar et al. [95]	Leuco dye-based TC ink
Jakovljevic et al. [74]	Leuco dyes and liquid crystal
Wu et al. [69]	3,3-bis(4 dimethylaminophenyl)-6 dimethylaminophthlate, 2,2-bis (4-hydroxyphenyl) propane and alepheticalkohol as thermochromic core materials, melamine formaldehyde
Candas and other researchers [66]	UV absorber and cross linker.
Hong [84]	Cholesteric liquid crystal
Guan and other researchers [55]	Cholesteric liquid crystal
Gilligan and associate researchers [28]	Cholesteric liquid crystal
Aguirre [39]	Colloidal photonic crystal
Nadia et al. [197]	Liquid crystal
Choudhury et al. [51]	Liquid crystal, resin binder
Christie et al. [77]	Liquid crystal
Christie et al. [91]	Leuco dye and liquid crystal
Maclaren et al. [83]	Crystal violet lactone dyes
Panak and other researchers [93]	Crystal violate lactone, bisphenol A, tetradecanol.
Yan and other researchers [98]	Inorganic pigment and luminous materials
Qu and researcher team [58]	PCM Ge ₂ Sb ₂ Te ₅
Geng et al. [54]	Nano particles
Ramig et al. tested [65]	Carbon nanotube
Kumar et al. [37]	Vanadium pentoxide
Wu [67]	Spirolactine color former, phenolic hydroxyl compound as color developer, 1-hexadecanol as PCM, gelatin, gum arabic
Geng et al. [54]	Nano particles
Ramig et al. [65]	Carbon nanotube
Kumar et al. [37]	Vanadium pentoxide
Dean et al. [154]	Thermochromic ink
White [141]	Cholesteric liquid crystal
Patel [140]	Liquid crystal
Kristina Bašneć [109]	Leuco dyes

References	Materials
Panak et al. [108]	Crystal violet lactone as a colour former, bisphenol A as a developer and tetradecanol as a co-solvent
Hulsey and his team [117]	Leuco dyes
Schubert et al. [114]	TiO ₂ /SiO ₂
Basnec and his researcher team [101]	Crystal violet lactone (CVL) dye, benzyl 4-hydroxybenzoate (B4HB) developer and 1-dodecanol (DD) solvent
Zhu [133]	Silica aerogel
Xiao et al. [132]	Vanadium dioxide (VO ₂), graphene/carbon nanotube (CNT)
Amin et al. [158]	Parafin as PCM, Fe ₃ O ₄ , CuO, TiO ₂ , and ZnO nanoparticles for improving latent heat. Fe ₃ O ₄ and CuO are black while TiO ₂ , ZnO are white.
Shibahashi et al. [165]	9-(diethylamino)-1-spiro 12-H-benzoaxan thene2, 1'(3'H)-isobenzofuran)-3'-one, bisphenol A, myristyl alcohol and stearyl caprate, epoxy resin-amine
Borque et al. [193]	A leuco dye, a phenolic colour developer
Larnet et al. [191]	Crystal violet lactone as dye; propyl gallate, octyl gallate or lauryl gallate as developer; 1-tetradecanol, 1-hexadecanol or 1-octadecanol as solvent.
Shibahashi et al. [157]	Crystal violet lactone, malachite green lactone, michler'shydrol, crystal violet carbinol etc.

3.3. Methods for Thermochromism

Table 3. Methods for thermochromism

References	Methods
Geng et al. [54]	Microencapsulation
Rao [24]	Coating
Jin et al. [60]	Wet Spinning
Potuck et al. [64]	Microencapsulation
Zhang et al. [72]	Melt Spinning
Wu et al. [69]	Microencapsulation
Wu et al. [69]	Coating
Feng et al. [30]	Coating & Microencapsulation
Krishna et al. [97]	Microencapsulation
Guan and other researchers [55]	Microencapsulation, electrospinning
Choudhury et al. [51]	Microencapsulation
Christie et al. [77]	Printing, Microencapsulation
Christie et al. [91]	Microencapsulation
Kumar et al. [37]	Coating
Bozhen Wu [67]	Microencapsulation
Sari et al. [79]	Microencapsulation, emulsion polymerization
Wilusz [85]	Microencapsulation, coating
Vikova [116]	Dyeing and Printing
Schubert et al. [114]	Coating
Xiao et al. [132]	Coating
Fujita et al. [156]	Microencapsulation
Shibahashi, Y., [157]	Microencapsulation Size: 2-30µm
Shibahashi et al. [165]	Microencapsulation, coating, interfacial polymerization
Patra et al. [34]	Coating and microencapsulation
LCR Hallcrest smart technology [122]	Color changing crystal and microencapsulation

3.4. Methods of Thermochromism Analysis

Table 4. Methods thermochromism analysis

Geng et al. [54]	Microscopic
Odwa et al. [57]	UV-Vis, DSC, XRD, TG
Jin et al. researchers [60]	Naked eye for color changing
Jin et al. [61]	SEM, XRD, DSC, TG, SEM
Ramig et al. [65]	Spectrophotometer, SEM
Brist et al. patented [70]	Visual
Zhang et al. [72]	SEM
Seren et al. [73]	Spectrophotometer
Candas et al. [66]	Spectrophotometer
He et al. [59]	HPLC
Hong [84]	Finite element
Guan et al. [55]	SEM, TEM, TG

Christie et al. [77]	Spectrophotometer
Chowdhury et al. [42]	Spectrophotometer
Lin et al. [145]	Spectrophotometer
Yan and other researchers [98]	XRD
Sari et al. [79]	SEM, DSC, TGA, DSC
Panak et al. [108]	Spectrophotometer
Bamfield et al. [126]	Spectrophotometer
Wen et al. [136]	Target detection by hyperspectral imagers
Volonakis et al. [143]	Target detection by human participants
Laren, et al. [191]	Diffuse reflectance spectrophotometry

3.5. Observations for Color Changing Parameters

Table 5. Observations for color changing parameters

References	Color changing parameters
Wilusz [85]	(100-200)°C, (5-15)°C
Salek et al. [55]	400°C, 600°C and 1000°C
Odwa et al. [57]	150°C
Jin and other researchers [60]	30°C-20°C
Yang jin [61]	Rose red at room temperature and colorless for blue light emission
Potuck et al. [64]	Between 33°C and 38°C
Martins [63]	10°C-60°C
Ramig et al. [65]	Bluer, redder
Ahmed et al. [52]	30°C, black to green
Zhang [71]	At 20°C, 45°C, 80°C, dark blue, light blue, 50 Times
Zhang et al. [72]	5°C and 35°C after 60 temp cycles
Seren et al. [73]	15°C and 31°C
Guan and other researchers [55]	Red to blue chromatic hue
Gilligan and researchers [28]	Color change reversible, controllable, and reproducible
Qu and researcher team [58]	30°C to 50°C
Wu [67]	100-time heating and cooling cycle
Burkinshaw et al. [82]	p ^H
Choudhury et al. [75]	Ultraviolet temperature, p ^H
Wilusz [85]	Color white to blue
Anne et al. [102]	Pitch length in liquid crystal and color changed
Basnec et al. [101]	Changes in the geometry of the material and color
Kulčar et al. [112]	Decolorized state at cooling for 10 hours
Jassim et al. [113]	Orange 30°C, Light orange 32°C, Light Pink 36°C, Colorless 41°C.
Tianzhi et al. [134]	Electrical field-based color changing
Fujita et al. [156]	Color changes from 5°C to 80°C
Shibahashi et al. [165]	Pink color below 25°C and colorless above 25°C

4. Camouflage Identification Methods

Adaptive camouflage can be investigated by spectroscopic, microscopic, photographic illumination and human participants as evidence of different branches of research and developments. Wen et al. [136] commented that target signature can be experimented by hyperspectral imagers and detection can be assessed in different distances [146]. Chang et al. [189] experimented that camouflage target can be identified at different angle of target. Gupta [163] remarked that spectral features can be detected the material properties of objects because of the emission, reflection, and absorption of light. Hyperspectral imaging can be used for photographic and spectral illumination in UV-Vis-infrared (IR) ranges [159,160,162,172,189]. Manolakis et al [181] experimented on hyperspectral image analysis for the operation and performance of detectors. Akkaynak et al. [170] suggested an image processing technique in perception science for color

calibration from digital camera. Animal scientists are doing camouflage research with hyperspectral imaging technology. Pinto et al. [182] successfully experimented on frog skin reflectivity in hyperspectral imaging between 400-2500 nm and spectral reflectivity between 700-1100 nm. Chiao et al. [180] investigated the color formation camouflage of cuttlefish with hyperspectral imaging technique. Akkaynak et al. [166] studied in color change for flounder camouflage with hyperspectral imaging Hultgren et al. [167] studied color change camouflage in marine isopod. Edelaar et al. [168] studied color changing of grasshopper. Russell et al. [173] experimented spectral camouflage of two crab species (*Portunus sayi* and *Planes minutus*) was assessed using hyperspectral imagery in 400-550 nm. Manolakis et al. [191] remarked that hyperspectral sensing can increase the detectability of pixel and subpixel size targets by exploiting finer detail in the spectral signatures of targets and natural backgrounds. Photographic illumination with digital camera and

hyperspectral camera, and its image analysis have versatile applications [171,179,185,186,200,201] including colored materials [187] but limited for camouflaging of textile-based target signature. Muller and Muller [196] studied that camouflage is a practicing issue of army operations in UV-Vis-IR spectrum. Reflection is a consideration of UV-Vis-IR ranges camouflage [183]. Hamilton et al. [184] performed liquid crystal analysis using CIE lab and image. Lin et.al confirmed that color analysis of camouflage can be investigated by CIE Lab color space in both specular [137] and diffuse components [148], its related calculation can be done by calorimetry [139,145]. Volonakis et al. [143] designed a human observer model for camouflage identification and its detection and recognition behavior was compared with human participants. Merilaita and other researchers [198] remarked that camouflage target influences target feature, edge, surface, and objects. Ruxton GD and researcher team [199] suggested that dorsum and ventral issues are responsible for background matching. Bhajantri et al. [195] developed a model of camouflage defect identification based on texture feature. Stenet et. al. [194] studied that background area selection for target detection influence the assessment of camouflage. Joe et al. [144] studied the eye movement behaviors on camouflage pattern which may influence the precision surveillance of detection when digital camera is used by different personnel.

5. Research Limitations and Development Approach for Thermal Camouflage

Defense professionals are working at different weather and diverse CB. Adaptive camouflage textiles with surrounding CB are great challenge of different situations. Sometimes defense soldier needs to shift urban to desert, desert to urban, urban to forest, forest to urban, forest to desert and desert to forest in a single operation and/or multi operations. Thermochromic colorant had been studied in literature for color changing but still researchers had not been studied the techniques for the suitability of camouflage purpose for modern surveillance technology and limited research have been observed for the suitability of simultaneous thermochromic and liquid crystal based textiles for color changing. Limited research had been found on adaptive camouflage textiles in literature, although sensor based preliminary stage research on adaptive camouflage textiles had been seen. But limited research on adaptive textiles has been reported for the color changing behaviors of textile substances in terms of details investigations of pitch length changing and wavelength changing of liquid crystal under heating mechanism, but the reviewed mechanism of thermochromism and liquid crystal have been positively argued for the feasibility of pitch length changing and wavelength changing of liquid crystal, thus the technology can be studied for the augmentation of color changing and adaptive camouflage textiles with thermochromic colorant and liquid crystal. Furthermore, adding liquid crystal-based technology for the adaptive camouflage textiles may generate an invention of proposed technology in Vis and IR spectrum of

camouflage technology for the concealment of modern surveillance technology including digital camera and/or hyperspectral camera.

6. Significant Approach for Adaptive Camouflage Textiles Technology

Burkinshaw et al. [138] remarked that concealment from day light surveillance is a most established practice of camouflage technology in which different hues are employed to overcome the contrast of object and its surrounding. Thermochromism in color changing is already being used in textiles and leather engineering but this is a new approach for the application in adaptive camouflage textiles by the simulation of heat-light-camouflage mechanism in terms of liquid crystal technique. Researchers studied thermochromism in color changing for high temperature based applications by using metallic particle finishing but the technology has limitations for clothing based applications where needs a comfort range of temperature but reversibility of color, numbers of color changing, numbers of sensitive temperatures, tolerance levels of human body temperature like 0°C to 45°C range or other purpose in different temperature ranges, suitable application of colorants in terms of heat and illumination, accurate thermochromism materials like nanoparticles and/PCM for sustaining thermochromism in color changing are still a hidden issue. Review shows that color changing application has been found for maximum two colors having a limitation with a very minimum temperature difference for clothing, but still the technology has not been used for camouflage. So proposed technology will have a temperature dissimilarity in different wavelength and different reflection in wavelength in terms of camouflage with surrounding background. Application of liquid crystal is not only limited to develop digital technology [142], textile and material scientists are also using liquid crystal for improving different technical properties on textiles substances but liquid crystal applications for the purpose of camouflage textiles are still in development stage/new to the textile and material scientists. Thermochromism mechanism can change the surface illumination in wavelength and color formation of textile substances. Liquid crystal can circulate in different angle when altering molecular orientation is occurred. No detailed studies have been observed for the illumination of color in different molecular orientations and its proposed effect of color changing in different wavelength. Thus, there is so much feasibility of doing liquid crystal-based camouflage textiles which may have an impact in the research and development of anti-surveillance technology in terms of designing and developing camouflage textiles. Figure 2 shows the adaptation of adaptive camouflage textiles with multidimensional surrounding CB. CB environments are illustrated as CB-01, 02, 03 and observers are termed as predator-01, 02, 03, 04. Adaptive camouflage textiles will be a single textile-based target signature, will be able to match with CB 01, 02, 03 under temperature versus chromatic replacement.

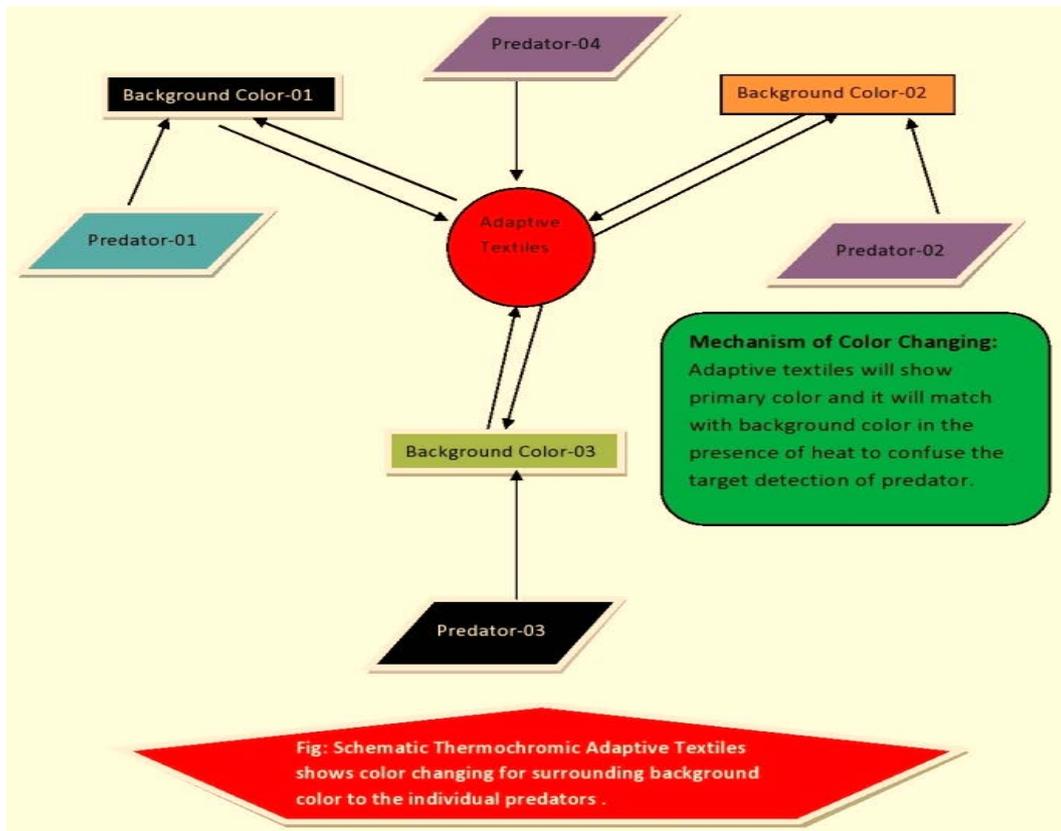


Figure 2. (Schematic) Thermochromic adaptive textiles shows color changing for surrounding background color to the predators or observers.

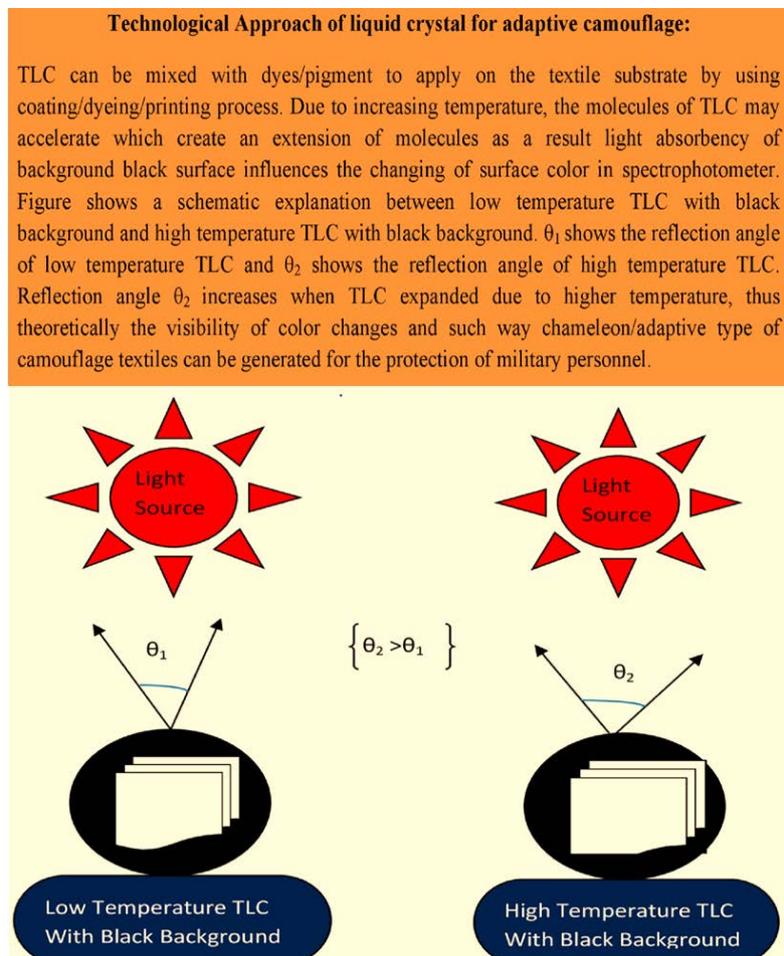


Figure 3. Principle of adaptive camouflage textiles coloration with thermochromic liquid crystal (TLC)

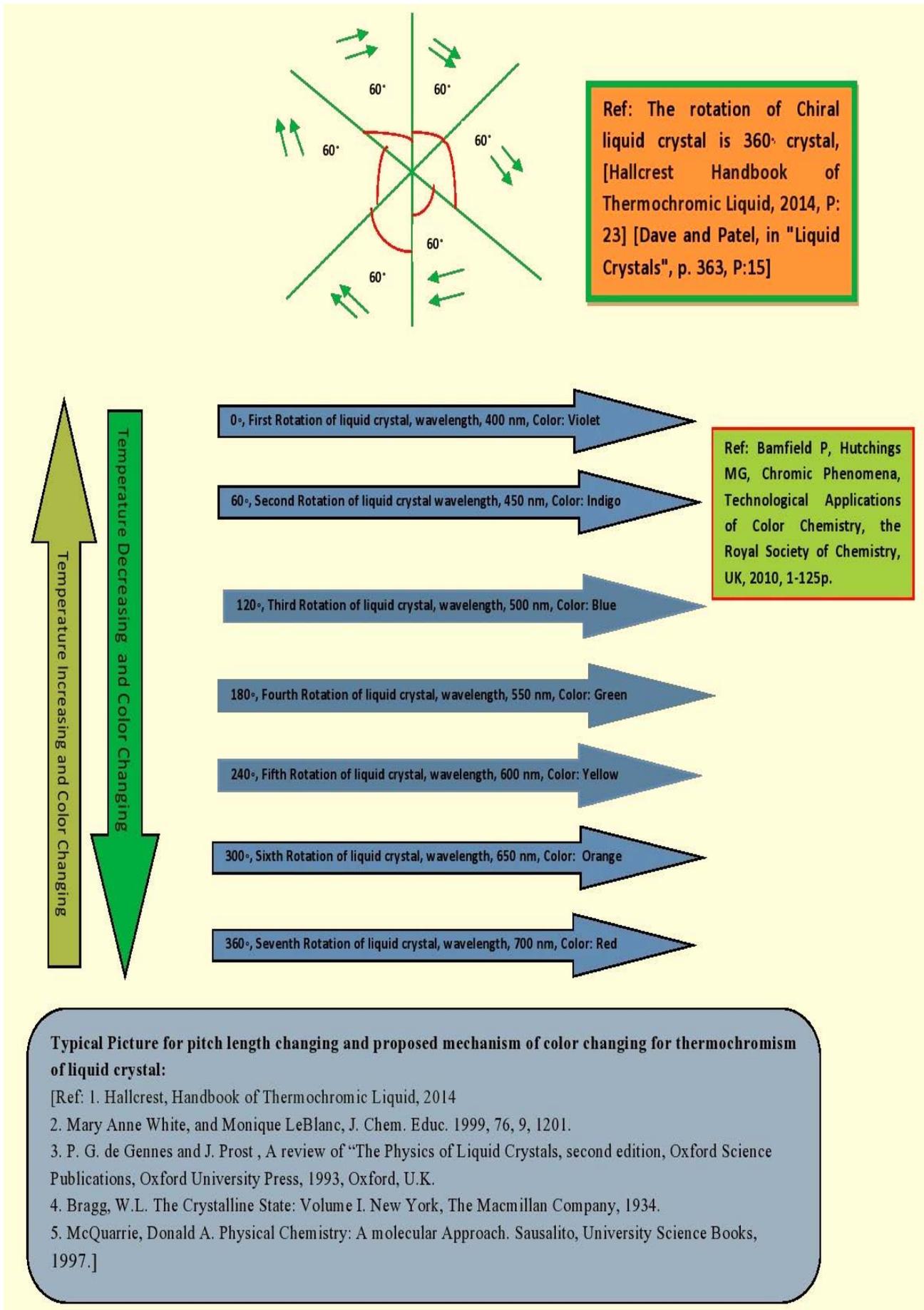


Figure 4. Typical principle for pitch length changing and chromatic replacement for thermochromism of liquid crystal

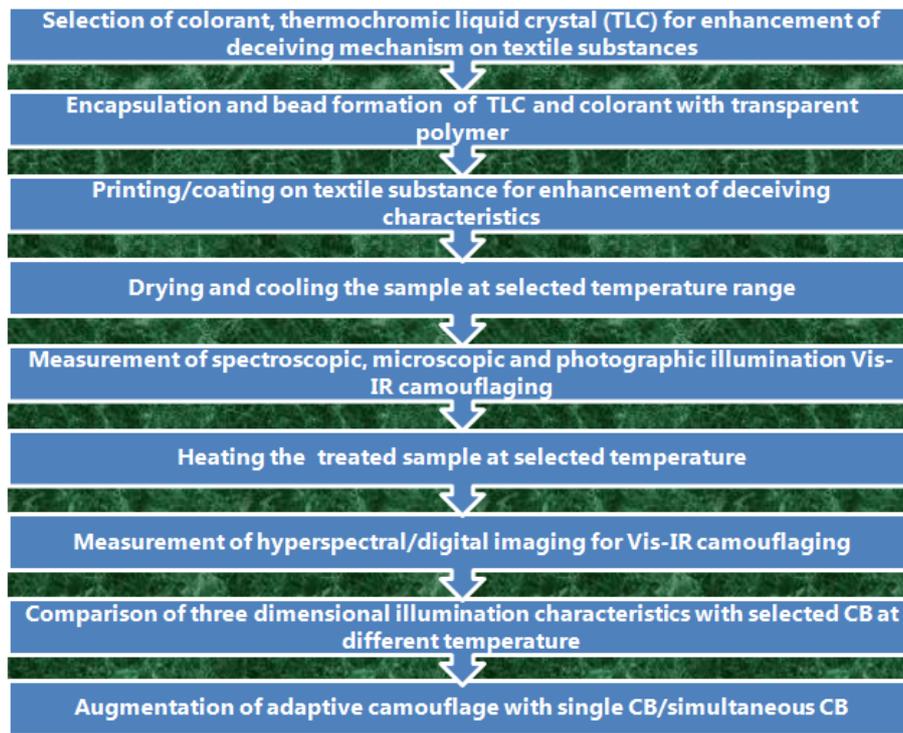


Figure 5. Proposed methodology for adaptive camouflage textiles formulation

7. Technical Approach of Liquid Crystal Mechanism for Adaptive Camouflage

Technical approach of adaptive mechanism [25,77,76,94] of liquid crystal have been demonstrated and interpreted in Figure 3. Established Bragg's law [104,105,106] has been used to signify the structure of color changing approach in liquid crystals molecules:

$$n\lambda = 2d\sin\theta, \lambda = 2d\sin\theta / n$$

where λ is the wavelength of the illumination Vis-IR ranges, d is the spacing of the liquid crystal layer (path difference of wavelength), θ is the incident angle (the angle between incident ray and the scatter plane), and n is an integer. By putting the value of d , θ and n , we can get the value of λ and the changing value of λ identify the replacement of wavelength and changing of wavelength clarify the altering of chromatic appearance of target signature. Thermochromism mechanism in liquid crystal will change the value of distance, d , the distance will change the angle, θ ; and wavelength λ will be changed which will create new reflection in specific temperature range and new color formation to the observer Figure 4 demonstrates the chromatic replacement principle by TLC mechanism. The order of molecular distance, angle of wavelength will be adjusted by temperature. Anne et al. [102] supported that the typical value of pitch length in liquid crystal phenomenon can be the order of wavelength can follow Bragg reflection theory. Therefore, color will change from black to red through orange, yellow, green, and blue, violet, and again black.

$$\text{Reflectance spectrum } (\lambda) = \frac{\text{reflected radiation at band } (\lambda)}{\text{incident radiation at band } (\lambda)}$$

Reflectance spectrum or spectral signature shows the function of incident energy, typically natural illumination such as sunlight, that is reflected by multidimensional CB material as a function of the wavelength (λ) of the energy [181]. Figure 5 signifies the proposed methodology for adaptive camouflage textiles formulation and design, applied by thermo-chromatic mechanism and coloration technique.

8. Conclusion

Liquid crystal shows precision of color change, but their color change range is limited. In contrast leuco dyes shows wider range of color but difficult to set with accuracy [125]. So, review can be strongly recommended for combined applications and formulations for thermochromic dyes and liquid crystal. Hypothesis of review undoubtedly states that there are enormous applications of thermochromism technology for color changing, liquid crystal mechanism for color changing and the combination of those techniques have been applied in different purposes for the development of color changing behaviors but the research and developments in the camouflage textiles applications have been limited. The technology of thermochromism and liquid crystal combination is not a new technology but the applications in camouflage and particularly in adaptive camouflage textiles are an original contribution in terms of leuco dyes, liquid crystal related to thermal engineering Adaptive camouflage for the surrounding CB and color matching is still a new technical approach for the implementation of defense professional. On the basis of review, it can be suggested that thermochromic liquid crystal can be implemented for future experimental study of adaptive camouflage, furthermore TLC based technology can be extended for the personal protection of different technical workers in extreme weather conditions including fashionable textile design although right formulation of liquid crystal

may spawn a new invention in the area of thermal camouflage engineering and its related branches of textile technology. Crystals mechanism of birefringence may split the refracted ray into two rays in anisotropic media [115]. The theory also can be applied for color changing of thermochromism and its feasibility with adaptive camouflage textiles. Proper percentage of liquid crystal (cholesteric liquid crystal, nematic liquid crystal and combination of both for color changing), appropriate selection of dyes (leuco dyes or other heat sensitive dyes), heating process for controlling and reversible process (conductive metallic yarn and/or nano particle, PCM), heating process for uncontrolling parameters (sun light) and a suitable process selection for textile coloration/finishing may generate expected color changing with surrounding and its right adaptation needs for the purpose of defense applications. Geometrical change will form an artificial wavelength and reflection on textile substances which is responsible for liquid crystal-based color changing process. Controlling geometrical change on temperature will create the expected color for adaptive camouflage textiles. Two reversible and irreversible color, multi-reversible and irreversible color, distance of temperatures and color changing, CB color and adaptive color can be developed by the controlling of rotation engineering and its pitch length of liquid crystal. A minimum percentage of liquid crystal needs to remain on the surface of textile substances for getting an outcome of pitch length changing, wavelength changing, color changing. Molecular size and distribution on the surface of textile substances will influence the surface modification in terms of heat changing, consequently wavelength changing and color changing accordingly. The amount of light scattered depends upon the size of molecules and the wavelength of light. Color change is occurred due to the absence of specific wavelengths of light reflected to the observer due to differences in molar absorptivity [31,107].

Nanoparticle/metallic-yarn/PCM/paraffin can be used for thermal storage in adaptive textiles for the camouflage formulation at different temperature. Research can be carried out by "Bisphenol A" free thermochromism process. Reflection can be changed artificially to the observer in UV-Vis-IR spectrum for making artificial confusion of target signature against surrounding CB environments. Color and temperature need to identify for thermochromism and color matching with surrounding CB. Color matching spectrophotometer can be applied for Vis camouflage, but the assessment of camouflage textiles with hyperspectral spectrometry and imaging is still new technology in review but animal scientists are also using hyperspectral camera for animal camouflage identification.

Declaration

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