Photoluminescent Printed Fabrics: An Innovative Solution to Natural Nightlight

Richa Sharma and Nilanjana Bairagi

Abstract Photoluminescent pigments are rare earth-based luminous materials activated by divalent europium. A photoluminescent pigment emits a bright phosphorous shade on excitation by daylight, incandescent, fluorescent, or ultraviolet light. It exhibits a high initial brightness and a long afterglow. Limited literature is available to guide textile and fashion designers on how these pigments can be used to create novel illuminated surface patterns. Patterns may be created of different intensity of luminescence for different application and products ranging from safety to fashion. Therefore, this research aims to systematically study the properties and design potential of photoluminescent blue pigments on textiles, printed by screen-printing method. The objective of this research is to study the effect of the concentration of photoluminescent pigments of different particle size on the emission of photoluminescence (luminosity and decay). The results are also correlated with the visual perception of photoluminescence by users in a nighttime environment.

Keywords Photoluminescent pigment · Scoptic light · Natural nightlight · Circadian cycle

1 Introduction

Photoluminescent (PL) pigments are rare earth-based luminous materials activated by divalent europium. These pigments possess remarkable characteristics such as extremely narrow emission bands and high internal quantum efficiencies. PL pigment emits a bright phosphorous shade on excitation by daylight, incandescent, fluorescent, or ultraviolet light. It exhibits a high initial brightness and a long afterglow. The effect of afterglow is dependent on the pigment concentration, surface area, and

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amount of radiant energy absorbed [1]. Although extensive research projects have explored ways of creating light emitting fabric displays using LEDs, electroluminescent wires, optical fibers, and embedded photoluminescent pigment in polymer fibers, limited experimental research has focused on the ways of designing a novel illuminated surface pattern using photoluminescent pigments in textile printing and fashion design [2].

There is a lack of detailed experimental study on the effect of the pigment concentration, light sources, substrate, and particle size and on the intensity of luminescence by the pigments. Limited literature is available to guide textile and fashion designers on how these pigments can be used to create novel illuminated surface patterns of different intensity of luminescence for different application and products ranging from safety to fashion.

Light is a powerful modulator of cognition [3–6] through its long-term effects on circadian rhythm and direct effects on brain function. Many sleep specialists suggest that this widespread exposure to blue light, long after the sun has set, is a major contributor to the modern epidemic of insomnia [7, 8]. Therefore, alternative sources of natural nightlight imitating moonlight or starlight, which does not retard the circadian cycle of humans, may be an area to be explored using PL printed textiles.

Therefore, the aim of the research is to study the effect of luminescence (luminosity and decay) emitted by different concentrations of photoluminescence pigments of different particle size, printed on textiles. The results are also correlated with the visual perception of photoluminescence by users in a nighttime environment.

2 Experimental Details

The luminosity of PL blue pigment was tested using a three-pronged approach. Initially, the absolute lux values were ascertained using an illuminometer (lux meter). As the lux values were below 1 lx, the second approach of time-resolved photoluminescence (TR-PL) spectroscopy was carried out to study the decay and intensity with higher precision. Additionally, visual perception study by user trials was undertaken to validate the above data in real-life environment.

2.1 Materials

The study was carried out on 100% ready to dye cotton fabric with both EPI and PPI of 68, thread count of 10 s Ne for both warp and weft and GSM of 290. The cotton fabric was printed with blue photoluminescent pigments of different particle sizes. The details and the given sample codes are presented in Table 1. The PL pigments were procured from supplier Jash Marketing Services, India, with the chemical composition, $Sr_4Al_{14}O_{25}$: Eu^{2+}, Dy^{3+} with a yellowish appearance exhibiting an aqua glow emission at λ max of 490 nm.

Table 1 Pigment and concentration matrix of blue PL pigments

S. No.	Pigment sample code	Particle size (μm)	Sample code for printed fabrics for variable concentration (%)				
			C5 (20%)	C4 (10%)	C3 (5%)	C2 (2%)	C1 (1%)
1	B4	50–60	B4C5	B4C4	B4C3	B4C2	B4C1
2	B3	45–55	B3C5	B3C4	B3C3	B3C2	B3C1
3	B2	25–35	B2C5	B2C4	B2C3	B2C2	B2C1
4	B1	10–15	B1C5	B1C4	B1C3	B1C2	B1C1

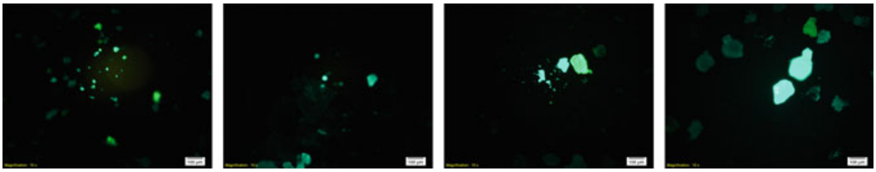

Fig. 1 Confocal images of photoluminescent pigment in variable particle size B1–B4 left to right

To study the effect of an increase in particle size, four pigments of blue series B1, B2, B3, and B4 have been chosen of variable particle size. The particle size was analyzed using confocal images as shown in Fig. 1. The particle size analysis was not successful as the pigment was not able to be stabilized in suspension.

2.2 *Printing with PL Pigments*

The fabric was industrially screen-printed (mesh size 200) with 1, 2, 5, 10, and 20% concentration of pigment in the print recipe. The curing was done at 120 °C. As presented in Table 1, the samples were coded for variable pigment size and concentration. A basic printing recipe consisting of pigment, commercial binder, fixer, and urea was used for printing.

The proposed usage of end products is for upholstery, drapes, and soft furnishings to facilitate interiors of home spaces to augment nightlight, and thus, the pigment concentration is taken on the higher range from 1 to 20%. The viscosity of the print paste was stable even at 20% pigment concentration.

2.3 *Evaluation of Intensity of Luminosity of PL Blue Pigment Using Illuminometer*

Illuminometer is a device used to measure lux of PL emitted by the samples as suggested in the literature [9]. The lux meter of brand HTC with a measurement range of 0–200,000 lx and resolution 0.01 + 3% lux was used to evaluate the intensity of the printed samples. The lux meter consists of a photon detector, which is connected to a selenium chip. The specimen is placed on a photon detector, which absorbs the photons emitted by the specimen.

Initially, the sample was kept in a dark room for two hours for the complete discharge of luminescence in line with similar trials conducted by Gulrajani et al. [9]. When the samples were measured after 2 h, without exposure to any excitation energy, no readings were exhibited by the lux meter. The sample was thus exposed to both UV and D65 lamp (closest to natural light) for a period of 1 h in a color cabinet prior to measurement. The exposure time was extended to 5 h subsequently to study the effect of exposure time on luminosity, but no appreciable increase in luminosity was recorded. Thus, for all further studies, exposure time of 1 h was maintained.

2.4 Time-Resolved Photoluminescence (TR-PL) Spectral Studies

Time-resolved photoluminescence spectral studies were conducted using high-resolution spectrophotometer QE Pro with scientific graphing, data analysis, and image processing computer tool Igor Pro. PL spectra, time scans, and lifetime study were undertaken to observe the irradiation from the PL pigments. Additionally, SEM and confocal imaging were carried out to observe the aggregation of the PL pigments on the printed samples.

The PL spectra for all the fabric samples have been recorded at 480 nm LED using single point light source of 220 V. This is the excitation wavelength as referred in the literature [10]. The experimental setup was a direct probe connected using fiber optics without any filters (so as to capture emission without any loss) to the fiber optic connected to spectrophotometer QE Pro equipped with Igor Pro, data management software to obtain spatial intensity maps and PL intensity time scans. The time-resolved photoluminescence (TR-PL) decay profiles for the PL pigments in the respective samples were observed at an integration time of 2 s/4 s sleep time over 60 data points and total time of 360 s. Thus, the decay was recorded for 360 s over 60 data points. As the PL intensity was very low, very high integration time of 2000 ms or 2 s was used. Due to high integration time and thus limitation of the system, the total no. of data points was limited to 60.

2.5 Visual Perception Study

The main objective of the study was to ascertain the visual perception of the samples printed with blue (B series 1–4) in scoptic light (dark room) environment with respect to change in concentration and overall perception (PL irrespective of the particle size).

A user-centric approach was taken to study the visual perception by users in real-life environment through rating of the luminosity of the samples. These observations were correlated with the experimental data.

The pilot study was conducted with ten participants. Eight boards were created with five samples of variable concentration for each board and randomly arranged. The color of the board chosen was black so that it does not interfere with the PL. The boards were kept in a room with both indirect sunlight and CFL and were exposed to about 5 h before the experiment was conducted. The perception rating was taken on a scale of 5 using the questionnaire with 5 being the best and zero being the least score. Scoptic lighting was maintained inside the room while recording data.

3 Research Findings

3.1 Effect of Pigment Concentration on the Luminosity of PL Pigment Printed Textiles

The luminosity at variable concentration of the blue PL pigment has been tabulated in the graph, Fig. 2. The *X*-axis depicts the concentration, and the *Y*-axis depicts the lux readings of the luminosity. Figure 2 depicts the increase in luminosity at respective particle size. B4 depicts the largest particle size of 50–60 μm, and B1 depicts the smallest particle size of 10–15 μm. It was observed that irrespective of the size of the pigment PL increases as the concentration of pigment increases in the print. This is seemingly the obvious outcome, and similar studies have been reported in the literature as well [11]. At 10 and 20% concentration, the PL intensity was the highest, with the average value being 0.05–0.15 lx. At lower concentrations of 1 and 2%, the intensity ranged from 0 to 0.02 lx. Particle size of about 10–15 μm gave the best results in PL, especially above 5% concentration.

The spectral image in Fig. 3 shows the decay of the PL printed textiles over a period of 360 s. The *X*-axis depicts the wavelength (nm), and the *Y*-axis depicts the time in sec. The color depicts the decay intensity. It is observed that pigment blue of wavelength 500 nm in the first 50 sec exhibits maximum intensity depicted by color blue which after 200 sec changes to yellow. We can clearly observe that the PL does not become nil, but reduces in intensity significantly. Figure 3 shows the spectral image of particle blue series B4 of the size 50–60 μm at three concentrations 5, 10, and 20%. Similar imaging is seen in other pigments as well. The spectral scans give the visual evidence of our previous findings with lux meter and thus evidently display the increase in PL with an increase in pigment concentration in the print paste.

TR-PL study for blue pigment B4 (50–60 μm) is presented in Fig. 4a, b. Figure 4a shows the intensity of PL versus wavelength, and Fig. 4b shows the exponential decay of PL intensity versus time. It can be observed that with the increase in the concentration of the pigment, the PL intensity increases at 500 nm for pigment B4. At 20% concentration, the intensity is almost two times of 10% pigment concentra-

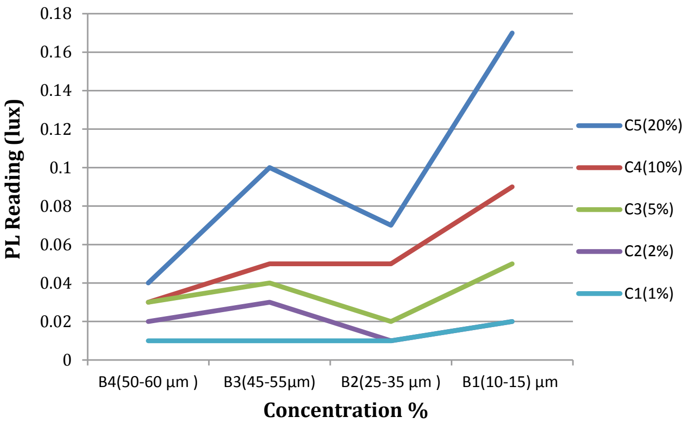

Fig. 2 Lux readings of PL pigment: blue

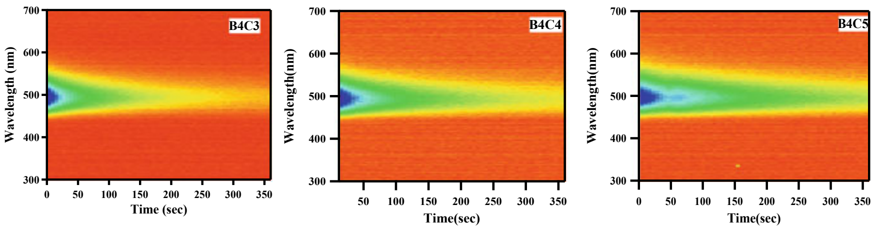

Fig. 3 Spectral image of B4C3, B4C4, and B4C5

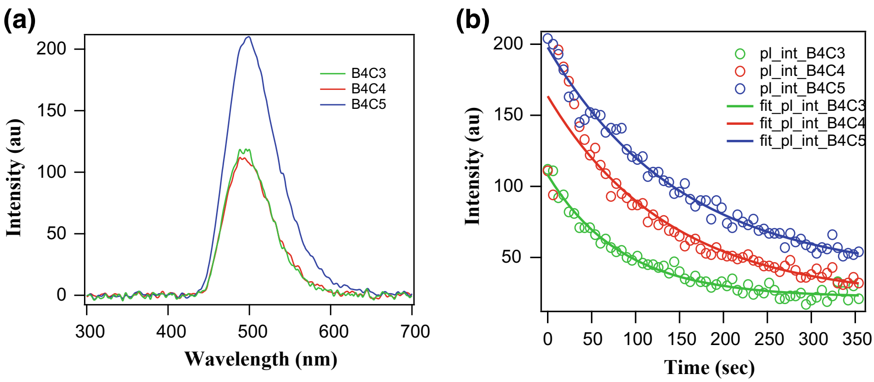

Fig. 4 **a**, **b** TR-PL study of blue pigment B4 with variable concentration

tion, and therefore, there is a direct correlation of pigment intensity with pigment concentration.

On the other hand, the TR-PL decay for pigment B4 as shown in Fig. 4b is an exponential curve, where luminosity does not become zero till the end but reduces exponentially in intensity. It can be correlated with the spectral scans, which show the initial high intensity in blue region. The luminosity curve plotted at variable concentration C3 (5%), C4 (10%), and C5 (20%) follows a similar path only the intensity increases with increase in concentration. Also, the intensity runs parallel to the time curve after the peak. This was correlated with user trials wherein even after 60 min the luminescence is perceptible by human eye. The study by Yan et al. [1] demonstrated the use of decay curves and spectral curves for their luminosity study.

The PL decay curve was again verified using a time-correlated photon counting (TCPC) of blue pigment B4 of particle size 50–60 μm. It was found that the path of the curve remains similar to the TR-PL study. Similar results have been plotted for blue pigments B2, B3, and B4 with particle size being constant and the variable component being the pigment concentration from C3 (5%), C4 (10%), and C5 (20%).

3.2 Effect of Pigment Particle Size on the Luminosity of PL Pigment Printed Textiles

To study the effect of pigment particle size on the luminosity, the studies were carried out with a constant pigment concentration of 20% (Fig. 5). The TR-PL decay follows an exponential curve similar to earlier results, where luminosity is highest at the start and gradually reaches a consistent level where it is sustained for longer period of time.

It was observed that the blue pigment B1, smallest particle size, was exhibiting the highest intensity. This may be attributed to the packing density and the structure of the PL particles on the printed samples. The surface-to-volume ratio, i.e., packing in a given volume, can be observed in the confocal microscopic image in Fig. 6. It is observed that the color of glow for blue pigments was bluish green. The confocal images clearly explain that the packing volume plays an important role in the lumi-

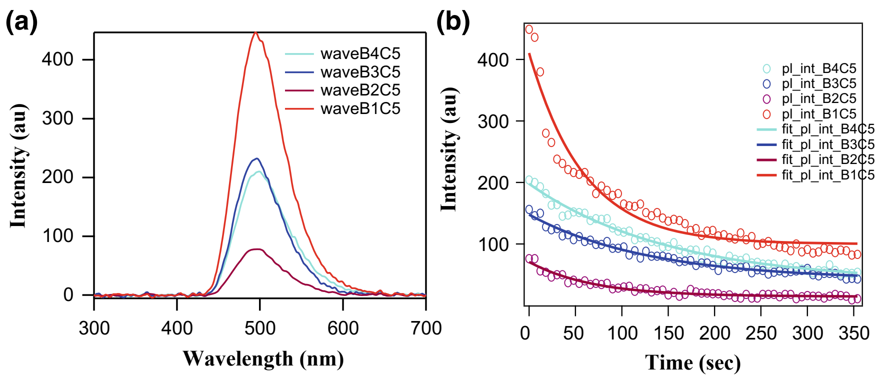

Fig. 5 **a**, **b** TR-PL of blue pigment blue with variable particle size at C5 (20%) concentration

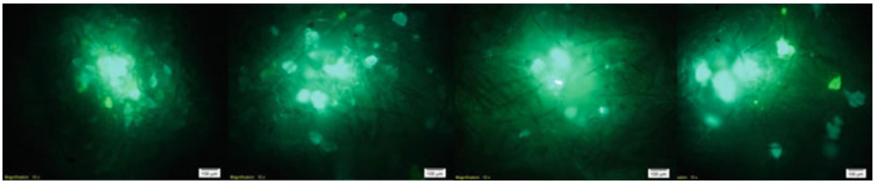

Fig. 6 Confocal images of blue pigment in increasing pigment size from left to right B1–B4 at constant exposure

Table 2 Time constant values of blue PL pigment with variable particle size at C5 (20%) concentration

S. No.	Pigment	Swatch code	Particle size (μm)	Tau (s)
1	B4	B4C5	50–60	151.43
2	B3	B3C5	45–55	129.8
3	B2	B2C5	25–35	68.75
4	B1	B1C5	10–15	59.1

nosity of the PL printed swatches, and lower particle size shall have the best packing volume and thus the best results [12]. Also stated by Hom, "the bigger particles by their orientation scatter the emitted light in undesired direction that reduces the emission intensity." Therefore, smaller particle size may perform better in luminous intensity.

The decay profile is single exponential curve with the experimental lifetimes (Tau) measured from the decay curves for all the swatches under investigation. Contrary to the luminosity readings, the time constant, Tau(τ) value as shown in Table 2, increases with increase in particle size, which means that the glow is sustained for longer time period as the size of the particle increases or

$$\text{Tau}(\tau) \propto \text{pigment particle size}$$

3.3 Effect of Visual Perception on the PL Printed Textiles

Literature survey indicates that the visual effectiveness at low adaptation states, i.e., mesopic and scoptic vision changes in a nonlinear fashion [13]. As per the recommended light levels [14], the lux captured in the samples ranges from overcast skies, starry night to a full moon. Thus, we find that the luminosity of the PL pigments falls in the range of mesopic and scoptic lighting [15, 16]. Visual perception with the user data analysis is presented in Fig. 7. The study clearly establishes that swatches with as low as C1 (1%) concentration with recorded luminosity of (0.01–0.02 lx) were also visually perceptible in spite of low concentrations as in the case of pigment B1, B2, and B4. At C3 (5%) and C2 (2%) level of concentration, it has been observed

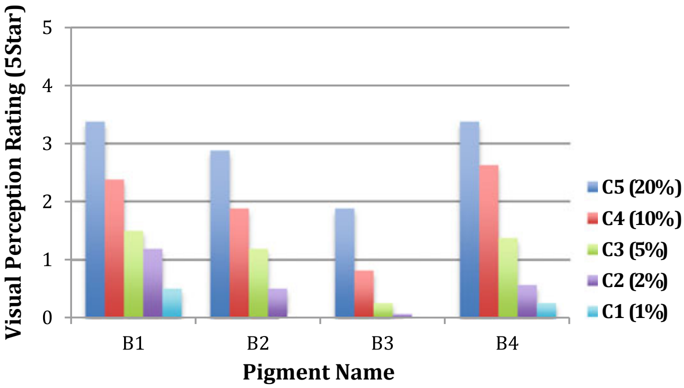

Fig. 7 Visual perception rating with change in concentration at variable particle size

that visible perception rating is low at 0.5–2.5 on a 5-point scale. At C4 (10%) and C5 (20%) concentration, the PL perception results were very good with the average value being 3–4 on a 5-point scale. PL pigment at C1 (1%) concentration has very low intensity and sometimes zero and thus can be ignored. As the concentration of pigment increases in the print, PL increases very evidently irrespective of the pigment. The visual effectiveness of pigment B1 and B4 of particle size (50–60 µm) and (10–15 µm), respectively, has the best rating.

Even though the lux values of the printed swatches is below 1 lx which is equal to starry night as per DIN67510 standard, it was observed that the user was able to perceive the PL even at lower concentration in low light conditions. Thus, intensity of luminescence on printed textiles may provide alternate light source so as to improve the impact of light cognition [3, 4, 7, 8] in comparison with conventional light sources.

4 Conclusion

It may be concluded that both pigment size and concentration play a significant role in the intensity of luminescence exhibited by the printed textiles. Increase in concentration of the pigment in the print paste increases the intensity of PL irrespective of the pigment size used as seen evidently in all three approaches, i.e., illuminometer, time-resolved spectroscopy, and visual perception study. At 10 and 20% concentration, the PL perception results were very good with the average value being 3–4 on a 5-point scale. The time constant (Tau) value increases with increase in particle size, which means that the glow is sustained for longer time period as the size of the particle increases. The visual effectiveness of PL blue pigment of particle size (50–60) and (10–15) µm, respectively, has the best performance rating. This is explained better with respect to surface-to-volume ratio, i.e., higher packing density decides the spectral intensity, and thus, we find that B1 (10–15) μm, though smallest in size, gives better performance when compared to rest.

Intensity of PL exhibits high initial brightness and a long afterglow and follows an exponential decay curve as seen in the TR-PL scans. The PL gradually reaches a consistent level, never touching zero, where it is sustained for considerable length of time. By increasing the exposure time/excitation time, it is observed that there is no appreciable change in the performance of the pigment. The time constant remains at the given range specific to the particle size. Even after the luminosity failed to be measured by the high precision instruments, the visual perception trials indicate that the human eye can still perceive the photoluminescence.

The non-visual effects of light on the circadian rhythm of humans have already been reported in the literature, and PL pigment printed textiles may provide the optimum luminosity to facilitate the circadian cycle. Thus, aqua glow from these blue PL printed textiles may play a key role in the design of lighting systems to optimize cognitive performance. Phosphorescent light emitted by PL pigments may be used as prints on textiles as alternative source of light.

The lux values of the printed samples were below 1 lx, which is equivalent to starry night as per DIN67510 standard. Even at low lux, the luminosity of the PL printed samples is visually perceptible by all the users. Therefore, PL printed fabrics may be used as an alternative for ambient lighting especially in areas inside homes for nighttime navigation. Thus, aqua glow from these PL printed textiles may play a key role in the design of lighting systems to optimize cognitive performance especially to facilitate easy and safe navigation in dark environment, especially for safety and preventive measures in edge definition and path illumination.

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