Synthesis and structural determination of fluoran

Le Hong Minh, Le Ngoc Hoan, Nguyen Minh Tri,
To Phuong Linh, Tran Minh Anh, Vu Ngoc Toan*

Institute of New Technology, Academy of Military Science and Technology, 17 Hoang Sam, Cau Giay, Hanoi, Vietnam.
*Corresponding author: vntoanchem@gmail.com
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ABSTRACT

Thermochromic materials have been widely applied in various civilian sectors, including textiles and healthcare, and hold significant potential for military applications. The prominent characteristic of these materials lies in their reversible color-changing ability in response to temperature variations. Among the compounds containing the xanthene moiety-a functional group commonly found in many dyes and pigments, fluoran stood out due to its high sensitivity in temperature-induced color transitions, particularly when combined with electron acceptors and suitable solvents. In this study, fluoran was synthesized via a two-step reaction involving phthalic anhydride, 3-diethylamino phenol, and p-bromophenol in toluene. The resulting product was a pink solid with a melting point in the range of 171 - 174 °C and a yield of 60,8%. The structure of the synthesized product was confirmed using advanced analytical techniques, including infrared spectroscopy (IR), one-dimensional nuclear magnetic resonance (1D NMR), and two-dimensional nuclear magnetic resonance (2D NMR).

Keywords: Fluoran; Xanthene; Thermochromic compound; Thermochromic material.

1. INTRODUCTION

Recently, materials capable of changing color in response to temperature variations have garnered significant attention due to their unique properties and potential applications. These include the development of thermosensitive luminescent fibers for anti-counterfeiting measures and various types of sensors [1, 8-10], thermal indicators, and dyes for solar cells. Extensive research has been conducted on temperature-responsive compounds, such as crystal violet lactone (CVL), spiropyrans, fluorans, and various inorganic complexes and polymers [2, 7, 9].

The xanthene structure serves as the fundamental structure for various dyes, including rhodamines, rosamines, thiofluoresceins, and fluorans. Among these, fluorans have been extensively studied using diverse methods and have gained significant attention for commercial applications in recent years alongside Crystal Violet Lactone (CVL) [3, 9, 10]. Recent studies on fluorans highlight their potential applications in various sensors and thermochromic compounds [4, 7, 8]. The 3*H*-spiro[isobenzofuran-1,9'-xanthen]-3-one structure exhibits thermochromic behavior when complexed with electron-accepting compounds (Bronsted acids) such as bisphenol A, *p*-cresol, and phenol in low-melting-point solvents like methyl stearate and hexadecanol. These complexes demonstrate reversible color changes with temperature, characterized by decolorization upon heating and color restoration as the temperature decreases. This reversible behavior underscores their potential for applications in temperature-responsive fabrics, particularly for camouflage purposes [8-10]. In 1995, Shen Meiqin et al. [5] synthesized 3-dimethylamino-7-(*o*-chlorophenyl amino)fluoran (fluoran black), while Wooram Oh and collaborators proposed a synthesis process for tert-butyl-substituted fluorans, achieving yields ranging from 18% to 85,8% [6]. However, these methods are constrained by relatively long reaction times, limiting their feasibility for large-scale production. Currently, domestic research on synthesizing thermochromic compounds remains underexplored. This article presents a simplified synthesis process and

structural analysis of thermochromic fluoran after synthesis, providing a foundation for its application on fabric surfaces for military camouflage purposes.

2. EXPERIMENT

2.1. Materials and equipment

Materials: 3-diethylaminophenol (99%, Xilong Scientific, China); anhydride phthalic (99%, Macklin, China); *p*-bromophenol (99%, Xilong Scientific, China); methansulfonic acid (99%, Acros, USA); sodium hydroxide (99%, Xilong Scientific, China); chlorhydric acid (37%, Duc Giang Co., Vietnam); Toluene (Fisher, USA); sulfuric acid (98%, Fisher, USA); potassium persulfate (99%, Xilong Scientific, China).

Equipment: The melting point (uncorrected) was measured using STUART SMP3 (BIBBY STERILIN-UK). The FTIR spectra were recorded on Tensor II Bruker (Germany) in KBr. The 1D and 2D NMR spectra were recorded on an Advance NEO (Bruker, Germany), and the NMR frequency was 500,247 MHz. Analytical balance 300 g, error ± 0,001 g (Labex, China); magnetic stirrer with heating, maximum stirring speed 1500 rpm, heating up to 370 °C (Velp ARE, Italy); filter paper Ø 18 cm (NewStar, China).

2.2. Process for the preparation of fluoran

The synthesis reactions of fluoran are shown below:

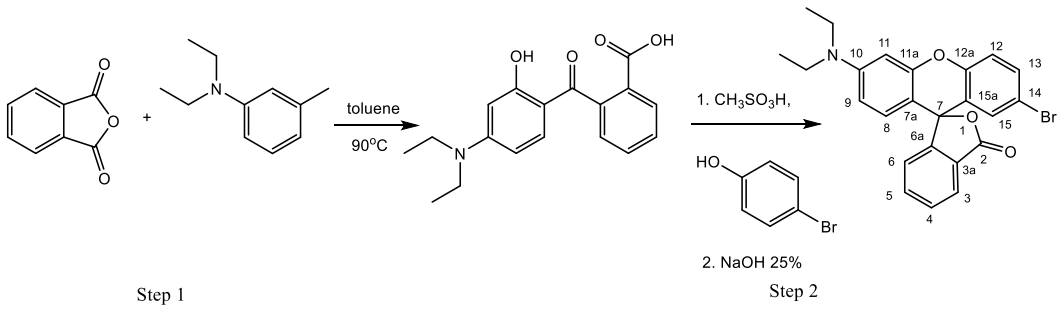

Figure 1. *Synthetic pathway for fluoran.*

- Step 1: A total of 3,3 g of 3-diethylaminophenol (20 mmol) and 3 g of phthalic anhydride (20 mmol) were transferred into a 100 mL two-necked round-bottom flask. The reaction mixture was heated to 110 °C under a nitrogen atmosphere until the mixture solidified. Then, 10 mL of toluene was added to the reaction flask. The mixture was heated at 90 °C for 5 hours. After that, the reaction system was cooled to 60 °C and stirred continuously for 1 hour. A 35% NaOH solution was then added dropwise using a dropping funnel until the pH of the reaction reached 11-12. The mixture was heated to 90 °C and maintained at this temperature for 2 hours, then was cooled to room temperature and slowly acidified with concentrated HCl to adjust the pH 4. A pink precipitate formed, which was collected by filtration using a Büchner funnel and washed with ultrapure water.

- Step 2: Prepared a solution by dissolving 3,13 g of synthesized solid and 1,73 g *p*-bromophenol in 25 mL methansulfonic acid. The solution was heated to 60-90 °C for 2 hours. After cooling to room temperature, 75 mL of 25% NaOH solution is added slowly over 60 minutes. The resulting pink solid was filtered by a Büchner funnel, washed with 50 mL water, and dried. A total of 2,73 g of fluoran was obtained (60,8% yield). The product was purified by column chromatography using a solvent system of petroleum ether: ethyl acetate (10:1), with a melting point of 171-174 °C.

3. RESULTS AND DISCUSSION

3.1. IR spectrum analysis results

In the IR spectrum, characteristic absorption bands are observed, confirming the presence of

functional groups in the product. Weak absorption bands in the range of 2900-2800 cm^{-1} are characteristic of the valence vibration ν_{C-H}. The strong absorption band at 1746 cm^{-1} represents the valence vibration of carbonyl group $\nu_{C=O}$ of the 5-membered lactone ring conjugated to the aromatic double bond. The strong absorption bands at 1627 and 1522 cm^{-1} are characterized by the $\nu_{C=C}$ bond vibrational value in the aromatic ring.

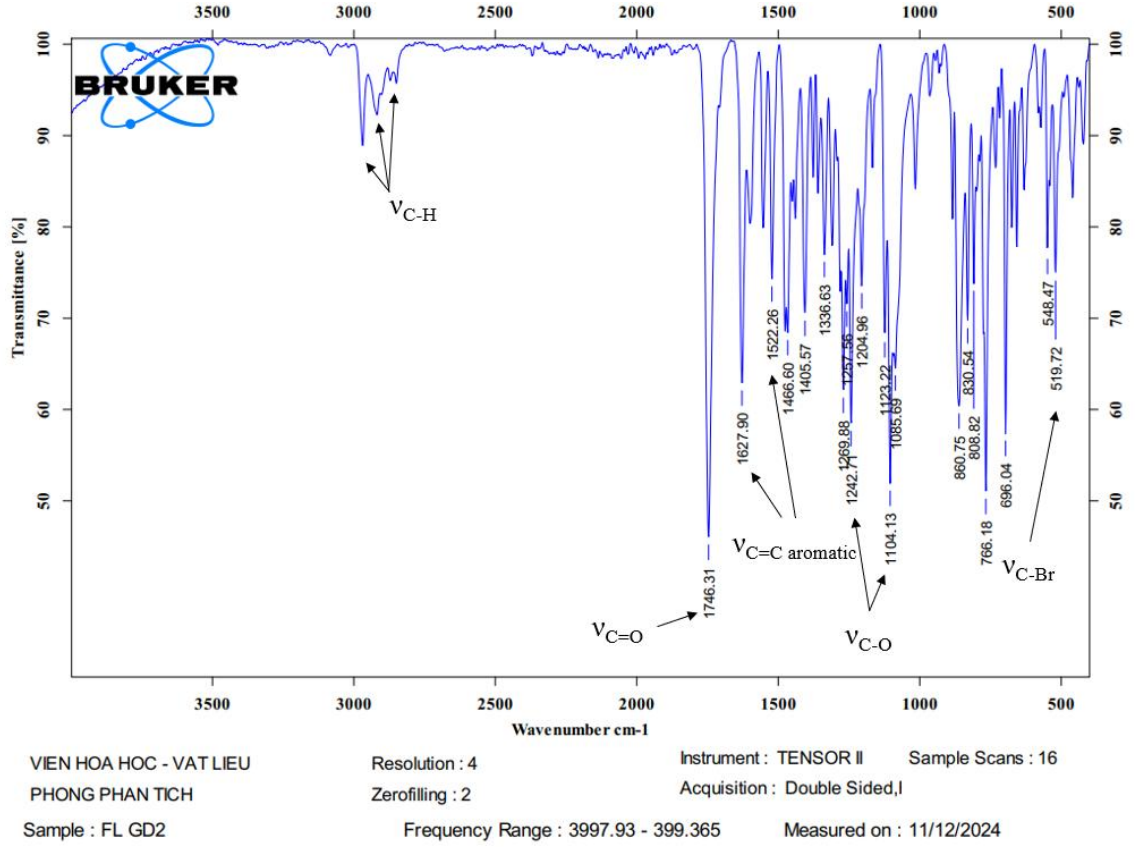

Figure 2. *The IR spectrum of fluoran.*

3.2. NMR spectrum analysis results

The assignment of protons and carbons in the molecule of fluoran is based on the following spectral data from figure 3 to figure 7:

- The weakest resonance signal appears at δ = 168,5 ppm and is assigned to carbon in the C=O group (lactone).

- ^{1}H-NMR (figure 3): The weakest resonance signal appears at δ = 8,02 ppm with doublet multiplicity and spin-spin interaction constants *J* = 7,5 Hz. It shows a long-range interaction with the carbon signal at δ = 168,5 ppm (C=O), and this proton can be assigned to H-3. This is crucial for identifying the other protons and carbons in the molecule.

- COSY: The resonance signal at δ = 8,02 ppm interacts with the resonance signal at δ = 7,74 ppm, allowing it to be assigned to H-4 (J = 0,5 Hz). In the HSQC spectrum, the signals at δ = 8,02 ppm (H-3) and δ = 7,74 ppm (H-4) show close interaction with the carbon atoms at δ = 124,9 ppm and δ = 130,4 ppm, respectively, which can be assigned to the carbon atoms at C-3 and C-4 respectively,

- HMBC: The resonance signal at δ = 8,02 ppm of proton H-3 shows a long-range interaction with the two resonance signals of carbon at δ = 151,8 ppm và 135,8 ppm. On the other hand, the

signal at δ = 151,8 ppm has a long-range interaction with the proton at δ = 7,81 ppm (*J* = 1 Hz), while the signal at δ = 135,8 ppm has no long-range with any other proton except proton H-3 at δ = 8,02 ppm. The resonance signal at δ = 7,81 ppm has a long-range interaction with the carbon signal at δ = 124,9 ppm (C=O). Thus, the signal at δ = 151,8 ppm can be determined to be C-6a, the signal at δ = 135,8 ppm can be determined to be C-5 and the proton signal at δ = 7,81 ppm belongs to H-5. The carbon signal δ = 130,4 ppm (C-4) has a long-range interaction with the proton at δ = 7,32 ppm (*J* = 7,5 Hz), so this proton signal can be attributed that this signal is from the remaining H-6 proton of the aromatic ring. The carbon signal at δ = 126 ppm has long-range interaction with two proton signals at δ = 7,74 ppm (H-4) and δ = 7,32 ppm (H-6); thus, it is assigned to C-3a. The proton signal at δ = 7,32 ppm (H-6) shows a long-range interaction with the carbon signal at = 82,4 ppm, which can be attributed to C-7.

- COSY: A pair of near H-H interactions of the two signals appear at δ = 7,65 ppm and δ = 7,35 ppm. The resonance signal at δ = 7,35 ppm is affected by the electron attraction from the –Br group, shifting towards the upfield region. As a result, the signals at δ = 7,65 ppm and δ = 7,35 ppm are assigned to H-13 and H-12, respectively. From these two proton signals, combined with the HSQC spectrum, we found 2 corresponding carbon signals of C-13 and C-12 at δ = 133,7 ppm and δ = 119,5 ppm.

- The carbon signal at δ = 150,3 ppm has a long-range interaction with three proton signals at δ = 7,65 ppm (H-13), δ = 7,35 ppm (H-12) and other proton signals at δ = 6,85 ppm (*J* = 2,5 Hz). Thus, the carbon signal at δ = 150,3 ppm can be attributed to C-14 and the proton signal at δ = 6,85 ppm belongs to H-15.

- The resonance signal at δ = 7,35 ppm of H-12 has a long-range interaction with two carbon signals at 121,5 ppm and δ = 114,8 ppm. On the other hand, the signal at tại δ = 114,8 ppm has a long-range interaction with the proton signal of H-15 at δ = 6,85 ppm, so this signal can be attributed to C-12a and the signal at δ = 121,5 ppm is C-15a.

- The resonance signal at δ = 6,48 ppm has a long-range interaction with the carbon signal of C-7 at δ = 82,4 ppm, so this signal can be determined to be the proton signal of H-8. Observing the HSQC spectrum, the proton signal at δ = 6,48 ppm has close interaction with three carbon signals at δ =128,5 ppm, δ =109,0 ppm δ = 96,9 ppm. It can be assigned that these are 3 carbon signals: C-8, C-9, C-11. The carbon signal at δ = 96,9 ppm has no long-range interaction with any other proton signal, so it can be attributed to C-8. The remaining two signals can be attributed to C-9 or C-11.

- The proton signal at δ = 6,48 ppm has a long-range interaction with two carbon signals at δ = 149,5 ppm and δ = 103,8 ppm. The resonance signal at δ = 103,8 ppm is affected by the electron expulsion into the ring from the N-$(CH_2CH_3)_2$ group, shifting towards the upfield region. Therefore, the carbon signals at δ = 149,5 ppm and δ = 103,8 ppm are assigned to C-10 and C-7a respectively. The last carbon signal of the aromatic ring at δ = 117,5 ppm is C-11a.

- The last carbon signal in the molecule at δ = 43,8 ppm and δ = 12,3 ppm are -CH_2 and -CH_3 of N-(**C**H_2**C**H_3)$_2$.

The HSQC and HMBC spectra of the product are presented in table 1.

Table 1. *HSQC and HMBC spectra data of fluoran.*

2D NMR ^{1}H-^{13}C HSQC of fluoran		**2D NMR ^{1}H-^{13}C HMBC of fluoran**	
Carbon-13 (δ, ppm)	**Proton (δ, ppm)**	**Carbon-13 (δ, ppm)**	**Proton (δ, ppm)**
135,8 (C-5)	7,81 (H-5)	168,5 (C=O)	8,02 (H-3)
133,7 (C-13)	7,65 (H-13)	151,8 (C-6a)	8,02 (H-3); 7,81 (H-5)

2D NMR ^{1}H-^{13}C HSQC of fluoran		2D NMR ^{1}H-^{13}C HMBC of fluoran	
Carbon-13 (δ, ppm)	**Proton (δ, ppm)**	**Carbon-13 (δ, ppm)**	**Proton (δ, ppm)**
130,4 (C-4)	7,74 (H-4)	150,3 (C-14)	7,35 (H-12); 6,85 (H-15)
129,8 (C-15)	6,85 (H-15)	149,5 (C-10)	6,48 (H-8)
128,5 (C-11 or C-9)	6,48 (H-11)	135,8 (C-5)	8,02 (H-3)
124,9 (C-3)	8,02 (H-3)	133,7 (C-13)	6,85 (H-15)
124,0 (C-6)	7,32 (H-6)	130,4 (C-4)	7,32 (H-6)
119,5 (C-12)	7,35 (H-12)	129,8 (C-15)	7,65 (H-13)
109,0 (C-11 or C-9)	6,48 (H-9)	126,0 (C-3a)	(H-4); 7,32 (H-6)
96,9 (C-8)	6,48 (H-8)	124,9 (C-3)	7,81 (H-5)
-	-	124,0 (C-6)	7,74 (H-4)
-	-	121,5 (C-15a)	7,35 (H-12)
-	-	114,8 (C-12a)	7,65 (H-13); 6,85 (H-15)
-	-	109,0 (C-9 or C-11)	6,48 (H-9,11)
-	-	103,8 (C-7a)	6,48 (H-9); 6,48 (H-11)
-	-	82,4 (C-7)	7,32 (H-6); 6,48 (H-8); (H-15)

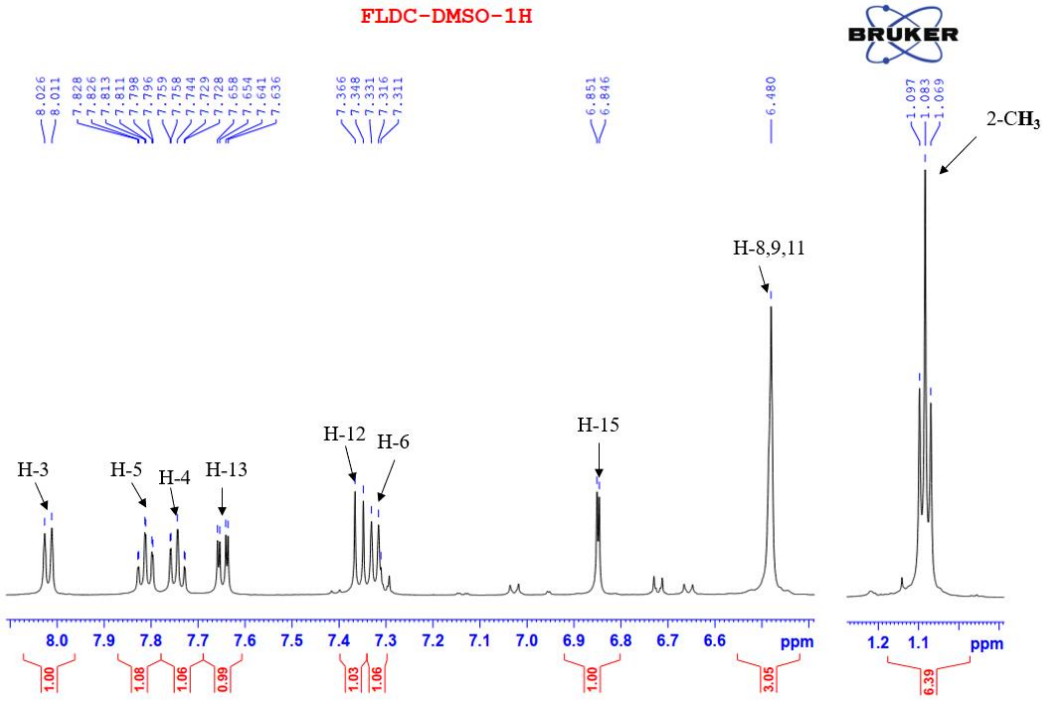

Figure 3. *^{1}H-NMR spectrum of fluoran.*

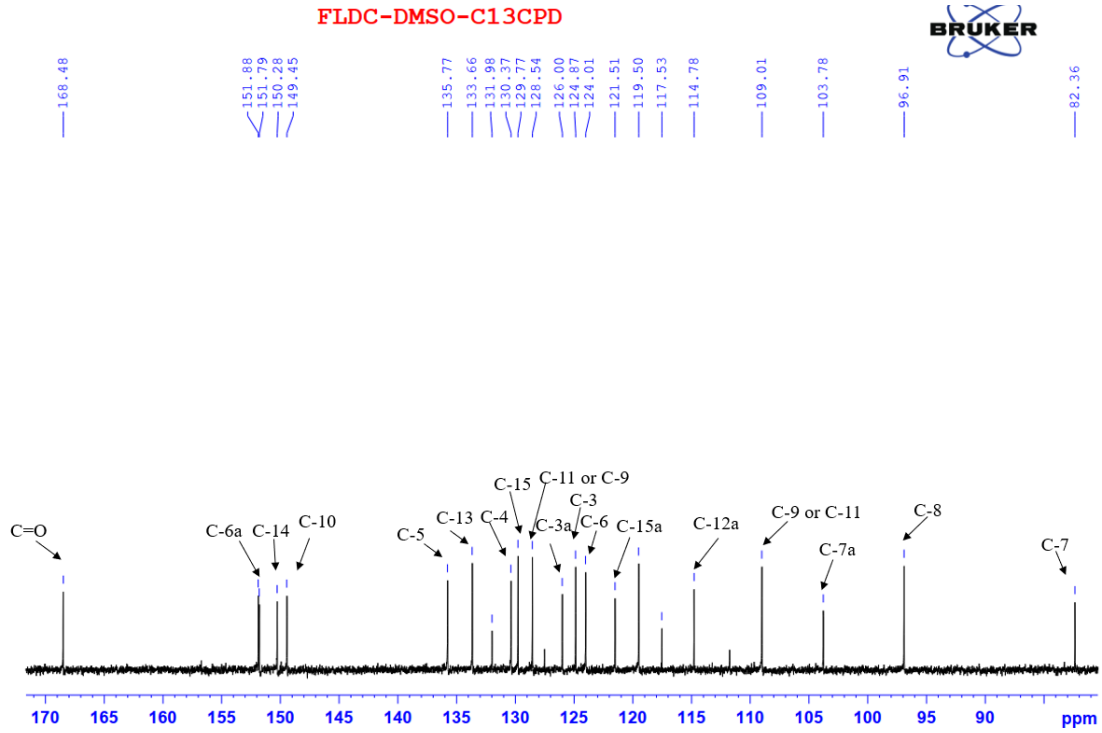

Figure 4. *^{13}C-NMR spectrum of fluoran.*

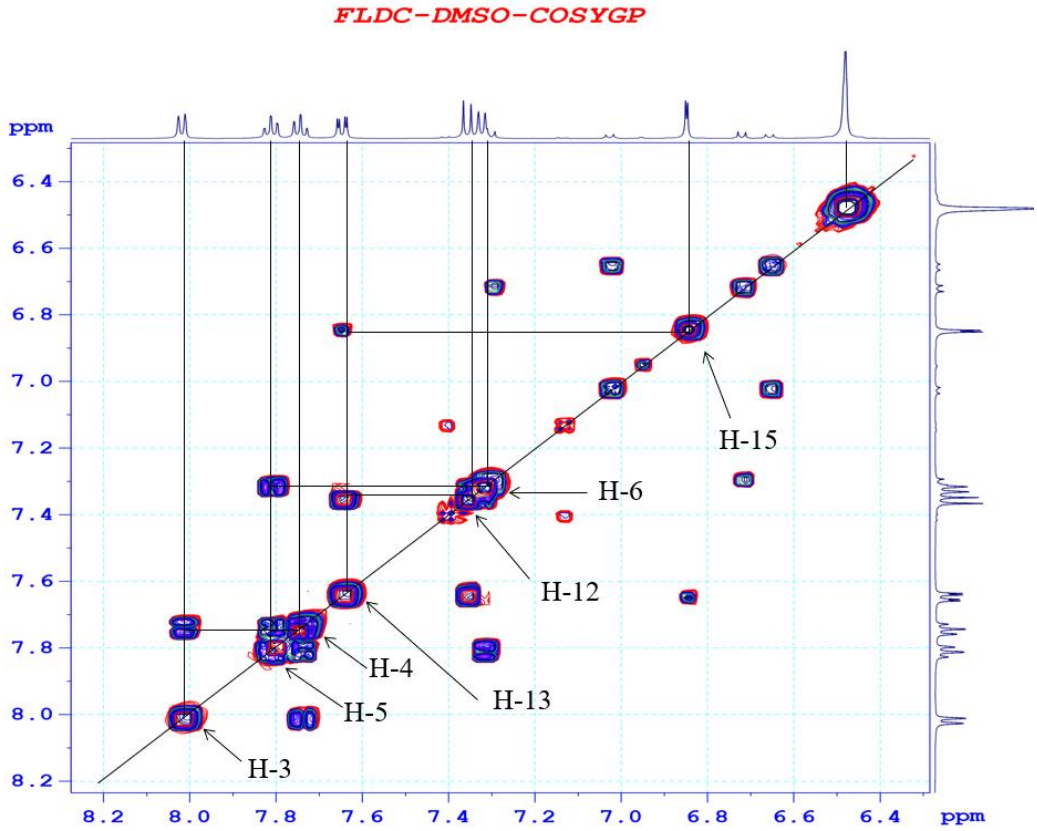

Figure 5. *COSY expansion spectrum of fluoran (aromatic region).*

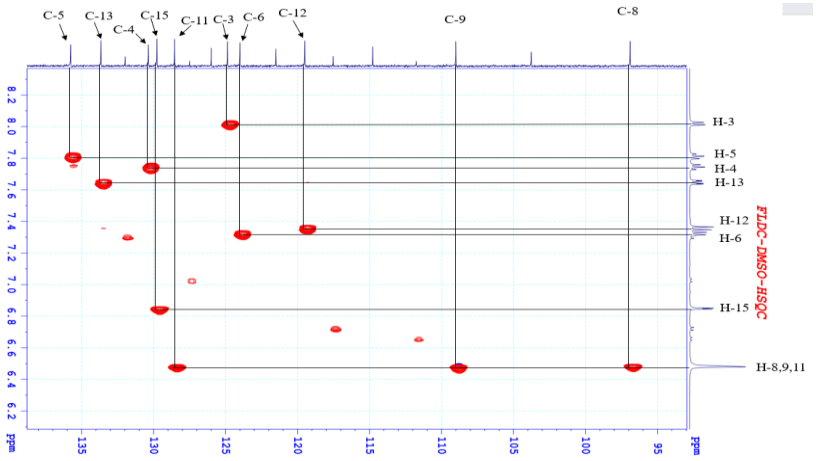

Figure 6. *HSQC expansion spectrum of fluoran.*

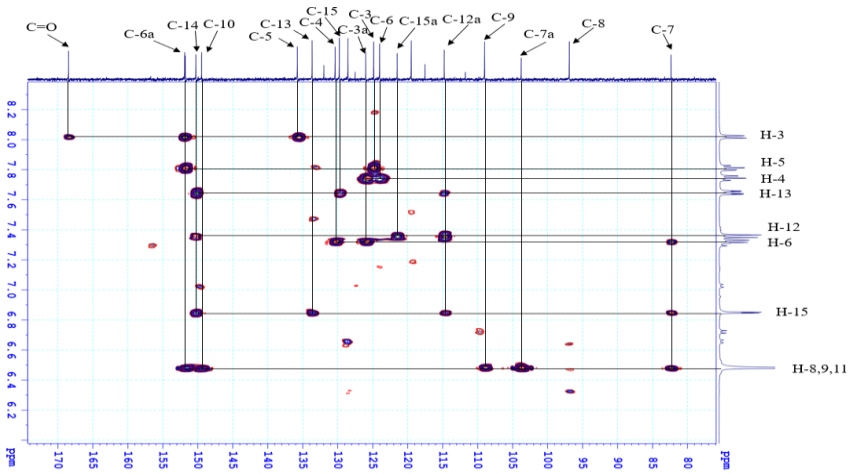

Figure 7. *HMBC expansion spectrum of fluoran.*

In the mass spectrum (MS) of the product (figure 8), a pseudo-molecular ion peak $[M+H]^+$ is observed at m/z = 450.0709, consistent with the calculated molecular weight of M = 449.06 Da, corresponding to the molecular formula of the product.

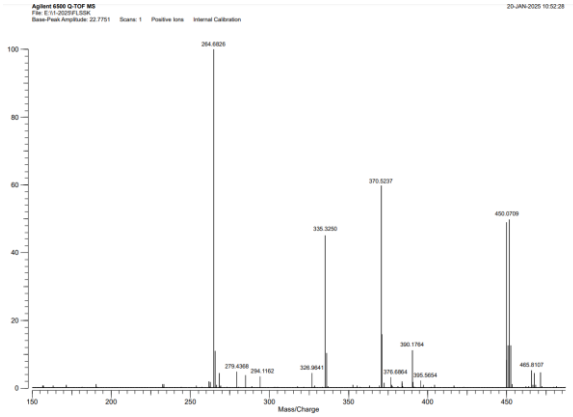

Figure 8. *MS spectrum of fluoran.*

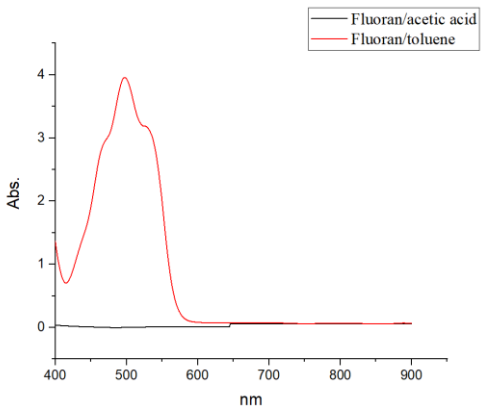

Figure 9. *UV-Vis spectrum of fluoran and proposed color generation mechanism.*

The results from the melting point, IR spectrum, ^{1}H NMR, ^{13}C NMR, COSY, HSQC, HMBC and MS spectra of the product confirm that fluoran was successfully synthesized and its structure was accurately determined.

When dissolved in a non-polar solvent like toluene, fluoran forms a clear solution, indicating that in a non-polar environment, the compound retains its colorless lactone ring structure. In contrast, dissolving fluoran in a polar solvent such as acetic acid results in a red-orange solution, likely due to the formation of a zwitterionic structure between fluoran and acetic acid. The UV-VIS spectrum of fluoran (figure 9) in acetic acid shows a strong, broad absorption peak at 500 nm. This maximum absorption band in the visible light region (green spectrum) suggests that the solution absorbs light at this wavelength, with its red color appearing as the complementary color to green on the color wheel.

4. CONCLUSIONS

The thermochromic compound fluoran was synthesized through a two-step reaction, yielding an average of 60,8%. The structure of the product was determined using modern spectroscopic methods. The results confirmed that the obtained product's molecular structure was consistent with the expected structural formula.

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TÓM TẮT

Tổng hợp và xác định cấu trúc của fluoran

Vật liệu nhiệt sắc (thermochromic materials) được ứng dụng rộng rãi trong nhiều lĩnh vực dân sự như dệt may, y tế,... và có tiềm năng ứng dụng trong quân sự. Tính chất đặc trưng của loại vật liệu này là khả năng thay đổi màu sắc theo nhiệt độ, nhờ vào sự hiện diện của các chất có tính năng đổi màu khi chịu tác động của nhiệt độ. Các hợp chất cơ sở xanthene được biết đến với nhiều ứng dụng trong sản xuất thuốc nhuộm, trong đó, fluoran nổi bật nhờ khả năng thay đổi màu sắc theo nhiệt độ với dải đổi màu rộng và độ nhạy cao khi có mặt chất nhận điện tử và dung môi thích hợp. Bài báo này trình bày quy trình tổng hợp chất nhiệt sắc fluoran thông qua phản ứng giữa phthalic anhydride, 3-diethylaminophenol và p-bromophenol trong toluene qua hai giai đoạn. Sản phẩm thu được ở dạng rắn màu hồng, nhiệt độ nóng chảy 171-174 °C, với hiệu suất đạt 60,8%. Cấu trúc của sản phẩm sau tổng hợp được xác định bằng các phương pháp hiện đại như IR, 1D NMR, 2D NMR.

Từ khóa: Fluoran; Xanthene; Chất nhiệt sắc; Vật liệu nhiệt sắc.