



Article Solution and Solid-State Optical Properties of Trifluoromethylated 5-(Alkyl/aryl/heteroaryl)-2-methylpyrazolo[1,5-*a*]pyrimidine System

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Abstract: This paper describes the photophysical properties of a series of seven selected examples of 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidines (**3**), which contain alkyl, aryl, and heteroaryl substituents attached to the scaffolds of **3**. Given the electron-donor groups and -withdrawing groups, the optical absorption and emission in the solid state and solution showed interesting results. Absorption UV–Vis and fluorescence properties in several solvents of a pyrazolo[1,5-*a*]pyrimidines series were investigated, and all derivatives were absorbed in the ultraviolet region despite presenting higher quantum emission fluorescence yields in solution and moderate emission in the solid state. Moreover, the solid-state thermal stability of compounds **3a**–**g** was assessed using thermogravimetric analysis. The thermal decomposition profile showed a single step with almost 100% mass loss for all compounds **3a** (72 °C), indicating low thermal stability for this series of pyrazolo[1,5-*a*]pyrimidines.

Keywords: pyrazoles; pyrimidines; pyrazolo[1,5-a]pyrimidines; photophysical properties

1. Introduction

According to the Web of Science, there have been about nine hundred publications on photophysical properties and organic compounds in the last five years [1]. This shows the importance of synthesizing organic compounds with these photophysical characteristics, which have drawn considerable attention and have been widely used in industrial and scientific fields [2].

For many organic molecules to exhibit outstanding photophysical properties, in most cases, a combination of factors is required, which are related mainly to their structural properties. These properties may involve the polarization of the chemical scaffolds due to the presence of electron-donating (EDG) and electron-withdrawing groups (EWG) [3], chain arrangements, and conformations (stereochemistry) [4–6], as well as the presence of charge-transfer bands, such as *intramolecular charge transfer* transitions (ICT) [7,8].

In this regard, *N*-heterocyclic skeletons present many classes of compounds that exhibit photophysical properties [9–12]. One such class is the pyrazolo[1,5-*a*]pyrimidines that have π -extended electronic systems by two planar fused rings with three nitrogen atoms of different electronic atom nature [13]; in fact, given its structural diversity, numerous studies have highlighted its importance in materials science [14–19].

For these reasons, this study sought to evaluate and study, for the first time, the photophysical properties of pyrazolo-pyridimine derivatives, more specifically, the compounds



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). named 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidines (**3**), where the synthetic approaches have already been mostly described in the literature [13,20,21], although there is still a lack of studies on the absorption and emission properties of these derivatives, both in solution and in the solid state. Given this context, UV–Vis absorption analysis and steady-state fluorescence emission properties, both in liquid and the solid state, will be discussed and studied. Furthermore, the solvent polarity on absorption and emission effects and the thermal stability in the solid state will also be discussed and presented (Scheme 1).



Scheme 1. Summary of this study: synthesis and photophysical properties of 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidines (3).

2. Materials and Methods

2.1. General

Unless otherwise indicated, all common reagents and solvents were used as obtained from commercial suppliers without further purification. The ¹H, ¹³C, and NMR spectra were acquired on a Bruker Avance III 600 MHz (**3a–g**) spectrometer for one-dimensional experiments with 5 mm sample tubes at 298 K and digital resolution of 0.01 ppm in CDCl₃ as the solvent, using TMS as the internal reference, and the atoms numbering according to Figure 1. All spectra can be found in the Supplementary Information (Figures S1–S8). All melting points were determined using coverslips on a Microquímica MQAPF-302 apparatus and are uncorrected. The HRMS analyses were performed on a hybrid high-resolution and high-accuracy (5 mL L⁻¹) micrOTOF-Q mass spectrometer (Bruker Scientifics, Billerica, MA, USA) at Caxias do Sul University (Brazil).



Figure 1. Atom numbering for NMR chemical shifts assignment of 3a-g.

2.2. Synthetic Procedures

General procedure was used for the synthesis of 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidines (**3a**–**g**).

According to Frizzo and collaborators [13], a solution of 3-amino-5-methyl-1*H*-pyrazole (1.0 mmol, 0.097 mg) (2) in acetic acid (5 mL) was added to a magnetically stirred solution of the respective 4-(alkyl/aryl)-4-methoxy-1,1,1-trifluoroalk-3-en-2-ones (1.0 mmol) (1a–g), also diluted in acetic acid (5 mL). The mixture was stirred at 80 °C for 16 h. After the reaction time (TLC), the products 3a–g were extracted with chloroform (3 × 10 mL), washed with distilled water (3 × 10 mL), and dried over anhydrous magnesium sulfate. The chloroform was removed in a rotary evaporator under reduced pressure and the respective compounds 3a–g were purified by recrystallization from ethanol.

2.2.1. 2,5-Dimethyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3a**) Yellow solid, yield 50%, m.p. 52–53 °C. Literature [20] (Yield 87%, oil)

¹H NMR (600 MHz, CDCl₃) δ (ppm): 6.96 (s, 1H, H-6), 6.52 (s, 1H, H-3), 2.67 (s, 3H, CH₃), 2.57 (s, 3H, CH₃).

2.2.2. 2-Methyl-5-phenyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3b**) Yellow solid, yield 85%, m.p. 123–124 °C. Literature [20] (Yield 82%, m.p. 123–124 °C). ¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.30–8.00 (m, 2H, Ph), 7.75–7.52 (m, 3H, H-6/Ph), 6.68 (s, 1H, H-3), 2.62 (s, 3H, CH₃).

2.2.3. 5-(4-Methoxyphenyl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3c**) Yellow solid, yield 60%, m.p. 182–183 °C. Literature [**2**1] ¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.09 (d, J = 8.6 Hz, 2H. Ph), 7.50 (s, 1H, H-6), 7.06 (d, J = 8.6 Hz, 1H, Ph), 6.62 (s, 1H, H-3), 3.92 (s, 3H, OCH₃), 2.60 (s, 3H, CH₃).

2.2.4. 5-(4-Fluorophenyl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3d**) Yellow solid, yield 98%, m.p.155–156 °C. Literature [20] (Yield 96%, m.p. 141–144 °C). ¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.12 (dd, J = 8.9, 5.3 Hz, 2H, Ph), 7.50 (s, 1H, H-6), 7.24 (t, J = 8.6 Hz, 2H, Ph), 6.66 (s, 1H, H-3), 2.61 (s, 3H, CH₃).

2.2.5. 5-(4-Bromophenyl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3e**) Yellow solid, yield 70%, m.p. 171–173 °C. Literature [13,20] (Yield 86%, m.p. 171–173 °C). ¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.00 (d, J = 8.6 Hz, 2H, Ph), 7.69 (d, J = 8.6 Hz, 2H, Ph), 7.50 (s, 1H, H-6), 6.68 (s, 1H, H-3), 2.62 (s, 3H, CH₃).

2.2.6. 2-Methyl-5-(4-nitrophenyl)-7-(trifluoromethyl)pyrazolo[1,*5-a*]pyrimidine (**3f**) Orange solid, yield 80%, m.p. 223–224 °C.

¹H NMR (600 MHz, CDCl₃) δ (ppm): 8.41 (d, J = 8.6 Hz, 2H, Ph), 8.32 (d, J = 8.8 Hz, 2H, Ph), 7.60 (s, 1H, H-6), 6.77 (s, 1H, H-3), 2.65 (s, 3H, CH₃).

¹³C{¹H} NMR (150 MHz, DMSO-d₆) δ (ppm): 157.8 (C-2), 152.1 (C-5), 150.2 (Ph), 149.1 (C-3a), 142.0 (Ph), 134.1 (q, J = 37.1 Hz, C-7), 128.1 (Ph), 124.2 (Ph), 119.4 (q, J = 274.8 Hz, CF₃), 102.4 (d, J = 4.2 Hz, C-6), 98.7 (C-3), 14.9 (CH₃).

HRMS (ESI): (M + H): Calcd. for $C_{14}H_{10}F_3N_4O_2 = 323.0756$; Found: 323.0759.

2.2.7. 2-Methyl-5-(2-thienyl)-7-(trifluoromethyl)pyrazolo[1,5-a]pyrimidine (3g)

Yellow solid, yield 72%, m.p. 155–156 °C. Literature [20] (Yield 89%, m.p. 152–154 °C). ¹H NMR (600 MHz, CDCl₃) δ (ppm): 7.73 (d, J = 3.6 Hz, 1H, thienyl), 7.58 (d, J = 5.0 Hz, 1H, thienyl), 7.41 (s, 1H, H-6), 7.19 (t, J = 4.4 Hz, 1H, thienyl), 6.60 (s, 1H, H-3), 2.59 (s, 3H, CH₃).

2.3. Photophysical Measurements

2.3.1. Photophysical Measurements in Solution

Electronic UV–Vis analysis of compounds **3a–g** in several solvents with distinct polarity (CH₃CN, CHCl₃, THF, toluene, EtOH, and DMSO) were measured using a Shimadzu UV2600 spectrophotometer (data interval, 1.0 nm, and slit 1.0 mm). Steady-state fluorescence emission spectra of derivatives **3a–g** in the same solutions were measured with a Horiba Jobin Yvon FluoroMax 4 Plus spectrofluorometer (slit 5.0 mm; Em/Exc) and corrected according to the manufacturer's instructions. Fluorescence quantum yield (Φ_f ; in %) values of compounds **3a–g** were determined by comparing the corrected fluorescence spectra with that of standard 9,10-diphenylanthracene (DPA) in CHCl₃ solution ($\Phi_f = 65\%$, $\lambda_{exc} = 375$ nm) according to the current literature [12,22–24].

2.3.2. Photophysical Measurements in the Solid State

For the absorption and UV–Vis measurements in the solid state, derivatives **3a–g** were treated as powder, and the baseline in the solid state was obtained using a barium sulphate standard (BaSO₄; Wako Company[®], Richmond, VA, USA). The diffuse reflectance spectra

(DRUV) were measured using an integrating sphere attachment on a Shimadzu UV-2600 spectrophotometer in the 250–700 nm range.

The fluorescence emission spectra in the solid state were measured in the 300–700 nm range using the Horiba Yvon-Jobin Fluoromax Plus (Em/Exc; slit 5.0 mm) instrument. Fluorescence quantum yields (Φ_f) in the solid state were determined by comparing the integrated area to the corrected fluorescence spectrum of compounds with the integrated area to the corrected fluorescence spectrum of a standard compound (in this case, sodium ascorbate – $\Phi_f = 55\%$), as reported elsewhere [23].

Fluorescence lifetimes in the solid state of related compounds were recorded using the time-correlated single-photon counting (TCSPC) method with DeltaHub controller and Horiba spectrofluorometer. Data were processed with the DAS6 and Origin[®] 8.5 software (Northampton, MA, USA) using mono-exponential fitting of raw data. NanoLED (1.0 MHz; pulse width < 1.2 ns; 284 nm excitation wavelength) was used as a source of excitation.

2.4. Thermogravimetric Analysis

Thermogravimetric analyses (TGA) were performed using a TGA Q5000 instrument (TA Instruments Inc., New Castle, DE, USA) at a heating rate of 10 °C min⁻¹, from 40 °C to 600 °C under a N₂ flux of 25 mL min⁻¹. The masses were approximately 1 mg for all samples. Data analysis was performed using the OriginPro 8.5 software (Northampton MA, USA). The confirmation of calibration of apparatus before analysis was done with CaC₂O₄·H₂O (99.9%).

Differential scanning calorimetry (DSC) analyses were carried out using a Q2000 DSC calorimeter (TA Instruments, New Castle, DE, USA) equipped with an RCS refrigeration accessory and with N₂ as purge gas (50 mL min⁻¹). The heating rate used was 5 °C min⁻¹. The calibration of instruments in standard DSC mode was verified with indium (99.99%). The masses of the samples (1–5 mg) were weighed on a Sartorius balance (M500P) with a precision of ± 0.001 mg. All samples were subjected to three heating–cooling cycles, as follows: 25 to 250 °C.

3. Results

3.1. Synthesis and Structural Characterization

The precursors 4-alkoxy-4-(alkyl/aryl/heteroaryl)-1,1,1-trifluoroalk-3-en-2-ones (**1a–g**) were first synthesized through the trifluoracetylation of enol ethers and acetals according to the literature procedures [25–33]. The 3-amino-5-methyl-1*H*-pyrazole precursor **2** was acquired from a commercial supplier (Sigma-Aldrich, São Paulo, Brazil).

The method employed to synthesize the 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidines (**3a–e**, **3g**) has already been described elsewhere [13]. The compounds (**3a–e**) and (**3g**) were obtained in 50–98% yields (Scheme 2), which showed the appearance of air-stable yellow-orange solids [13,20,21]. The compound 2-methyl-5-(4-nitrophenyl)-7-(trifluoromethyl)pyrazolo[1,5-*a*]pyrimidine (**3f**) has yet to be described in the literature, and it was obtained in 80% yield after recrystallization (also from ethanol).

All products were fully characterized with ¹H NMR and the melting point showed spectral data typical for these compounds and also in agreement with the literature [13,20,21]. Until now, an unpublished compound (**3f**) was also characterized by ¹H- and ¹³C NMR and HRMS. For instance, in the NMR chemical shifts assignment, compound **3f** presented a chemical shift at 7.60 ppm at the ¹H NMR spectrum, which was assigned to the pyrimidine H-6; a signal at 6.77 ppm was assigned to the pyrazole H-3, a signal at 2.65 ppm referred to the unique methyl substituent, and a signal at 8.41 and 8.32 ppm was assigned to the p-phenyl substituted aromatic ring. The same compound **3f** showed chemical shifts in the ¹³C{¹H} NMR spectrum as a singlet at 157.8 (C-2), 152.1 (C-5), 149.1 (C-3a), 102.4 (C-6) and 98.7 (C-3) ppm, and a quartet for C-7 and CF₃ group appearing at 134.1 ppm with J = 37.1 Hz and 119.4 ppm with J = 274.8 Hz, respectively, due to the ¹³C–¹⁹F scalar coupling.



Scheme 2. Synthesis of 5-(alkyl/aryl/heteroaryl)-2-methyl-7-(trifluoromethyl)pyrazolo[1,5-a]pyrimidines (3).

3.2. Photophysical Properties of Pyrazolo[1,5-a]pyrimidines (3a–g)

3.2.1. Solution Analysis

Regarding the photophysical properties of pyrazolo derivatives **3a–g**, the photophysical properties of all compounds in different solvent polarities (toluene, CHCl₃, CH₃CN, THF, EtOH, and DMSO) were analyzed. For exemplification purposes, the spectral profile of derivative 3b in all solvents studied is illustrated in Figure 2, and the absorption parameters of compounds are listed in Table 1; all UV–Vis absorption spectra are listed in the Supplementary Information (Figures S9–S14).

In general, all derivatives showed electronic transition bands in the UV region and can be attributed to $\pi \to \pi^*$ and $n \to \pi^*$ type transitions, which are characteristics of this type of heterocyclic and aromatic skeleton, according to the literature [12,23,24,34]. As seen in Figure 2, the derivatives studied show a similar absorption behavior according to the nature of the solvent. Additionally, by analyzing the UV–Vis spectra in the ground state of related compounds, small changes according to the solvent property are also observed, and some spectral changes occur due to the presence of electron-donor or -acceptor substituents (Table 1).



Figure 2. Comparative UV-Vis absorption spectra in several solvents of compound 3b.

Compound	Solvent ^a	λ_{abs} , nm (ϵ ; M $^{-1}$ cm $^{-1}$)	λ_{em} , nm (QY, %) ^b	SS (nm/cm ⁻¹) ^c
3a	CHCl ₃	274 (15670); 309 (4850)	501 (67.0)	192/12,400
	THF	273 (19870); 308 (4505)	473 (87.0)	165/11,325
	Toluene	283 (16120); 309 (8870)	492 (92.0)	183/12,040
	CH ₃ CN	306 (12550); 337 (7150)	511 (67.0)	174/10,105
	EtOH	305 (17500); 338 (9690)	456 (55.0)	118/7655
	DMSO	307 (9995); 342 (5120)	441 (86.0)	99/6565
3b	CHCl ₃	266 (22520); 325 (7320); 357 (sh)	504 (79.0)	147/8170
	THF	256 (30195); 324 (13535); 362 (sh)	507 (78.0)	145/7900
	Toluene	286 (19550); 331 (15950); 362 (sh)	508 (88.0)	146/7940
	CH ₃ CN	265 (20210); 324 (3800); 360 (sh)	506 (71.0)	146/8015
	EtOH	265 (21035); 325 (4175); 365 (sh)	514 (71.0)	149/7940
	DMSO	269 (17410); 328 (3570); 362 (sh)	521 (91.0)	159/8430
3c	CHCl ₃	290 (13420); 338 (5785); 367 (sh)	500 (77.0)	133/7250
	THF	256 (18080); 295 (23610); 339 (12985); 368 (sh)	500 (75.0)	132/7170
	Toluene	294 (22040); 338 (19095); 365 (sh)	501 (84.0)	136/7435
	CH_3CN	287 (14085); 324 (3800); 360 (sh)	554 (63.0)	194/9730
	EtOH	289 (11740); 337 (5285); 367 (sh)	487 (56.0)	120/6715
	DMSO	269 (10020); 327 (2010); 364 (sh)	509 (88.0)	145/7825
3d	CHCl ₃	269 (15780); 331 (2870); 370 (sh)	504 (79.0)	134/7185
	THF	256 (17380); 288 (8800); 326 (9640); 362 (sh)	509 (77.0)	147/7980
	Toluene	289 (18920); 336 (6020); 369 (sh)	510 (87.0)	141/7490
	CH ₃ CN	266 (20720); 325 (4070); 359 (sh)	516 (73.0)	157/8475
	EtOH	267 (17185); 328 (3030); 360 (sh)	514 (73.0)	154/8320
	DMSO	269 (15720); 327 (3125); 359 (sh)	521 (93.0)	162/8660
3e	CHCl ₃	276 (17465); 330 (3800); 364 (sh)	507 (79.0)	143/7750
	THF	257 (9915); 291 (9720); 329 (8275); 365 (sh)	511 (78.0)	146/7830
	Toluene	290 (22170); 334 (15485); 362 (sh)	510 (87.0)	148/8015
	CH ₃ CN	272 (10370); 327 (2195); 364 (sh)	516 (73.0)	152/8090
	EtOH	274 (20375); 327 (4695); 366 (sh)	514 (73.0)	148/7865
	DMSO	275 (17760); 330 (4285); 366 (sh)	524 (90.0)	158/8240
3f	CHCl ₃	299 (10955); 344 (sh)	496 (64.0)	152/8910
	THF	271 (10545); 296 (12640); 342 (sh)	524 (73.0)	182/10,155
	Toluene	297 (11850); 346 (sh); 382 (sh)	520 (89.0)	138/6950
	CH ₃ CN	295 (11625); 341 (sh); 373 (sh)	545 (70.0)	172/8460
	EtOH	292 (17630); 340 (sh); 373 (sh)	419 (24.0)	46/2940
	DMSO	257 (14555); 301 (16145); 347 (sh)	558 (95.0)	211/10,900
3g	CHCl ₃	280 (19115); 337 (8370); 375 (sh)	481 (63.0)	106/5875
	THF	257 (15280); 304 (20765); 336 (19370); 378 (sh)	511 (75.0)	133/6885
	Toluene	290 (17520); 345 (8170); 375 (sh)	510 (86.0)	135/7060
	CH ₃ CN	276 (11520); 343 (5715); 372 (sh)	517 (73.0)	145/7540
	EtOH	278 (18050); 343 (8620); 371 (sh)	496 (56.0)	125/6790
	DMSO	281 (21175); 346 (11215); 375 (7770)	520 (89.0)	145/7435

Table 1. Photop	ohysical data anal	ysis of derivatives 3a –	g in different solv	ents
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^a Dielectric constant (ε) and refractive index (η): toluene (ε = 2.38; η = 1.4969), THF (ε = 7.50; η = 1.4072), CHCl₃ (ε = 4.81; η = 1.4459), CH₃CN (ε = 36.6; η = 1.3441), EtOH (ε = 24.5; η = 1.3614), and DMSO (ε = 46.7; η = 1.4793); ^b Excited at lower transition band and using 9,10-diphenylanthracene (DPA) in chloroform as standard (λ_{exc} = 375 nm; Φ_f = 0.65); ^c Stokes shifts: $\Delta \lambda = \lambda_{em} - \lambda_{abs} = 1/\lambda_{abs} - 1/\lambda_{em}$; sh = sholuder.

By comparing the electronic effect of the substituent on the aromatic moiety (3c—OCH₃ and 3f—NO₂ units), very subtle shifts can be observed in the other solvents investigated, revealing that there is no significant change in the ground state (Table 1).

Regarding fluorescent emission properties, derivatives **3a–g** were investigated in the same solvent polarities used in the UV-Vis analysis, and the data regarding the emission peaks (λ_{em}), quantum fluorescence yield (QY), and Stokes shifts (SS) are presented in Table 1. The normalized fluorescence emission spectra of derivatives in all solvents are presented in the Supplementary Information (Figures S15–S20). Regarding the fluorescence

lifetime measurements of the derivatives in solution, time-resolved measurements were not made because the proper NanoLED source was unsuitable for this analysis.

In general, derivatives **3a–g** have emission bands located in the blue to green range. As with the UV–Vis absorption analysis, compound **3b** was chosen as an example, and the fluorescence emission spectra in all solvents and natural/UV light solution photography are listed in Figure 3. According to the spectra in Figure 3c, the solvent polarity does not show any significant changes in the emission peaks of compound **3c**. As for compound **3f** (containing NO₂ group), more visible changes are observed, mainly in the protic medium (Supplementary Information—Figure S24). We can attribute this to a difference in the stabilization of the structures in the excited state, primarily in the presence of electron-withdrawing groups and the secondary H-bonding interactions in ethanol solution.





Figure 3. (a) Solutions in natural light, (b) solutions in UV_{365nm} light irradiation, and (c) comparative steady-state fluorescence emission spectra in several solvents of compound **3b**.

As for the Φ_f values, the compounds presented higher QYs; this may be associated with a greater stabilization and solvation of these molecules in the singlet excited state (Table 1) and dependence on the substituent electronic property. Finally, moderate to large SS were observed for all derivatives in the solvents studied, and this can be attributed to

the vibrational relaxation or dissipation and solvent reorganization, which can decrease the separation of the energy levels of the ground and excited states (Table 1).

3.2.2. Aggregation-Induced Emission Behavior

In a generalized way, the aggregation-induced emission (AIE) phenomenon describes the behavior of a molecule that shows dim or no emission in dilute solution but muchenhanced emission in aggregates or the solid state [35,36]. The fluorescence emission behaviors of the selected compounds **3b**, **3c**, and **3f** were examined in the THF-H₂O mixture (0–90% water fraction) to confirm the possibility of AIE characteristics. Studied compounds emit a blue to green region under a UV lamp with 365 nm in THF solution (Figure 3). All fluorescence emission spectra in the THF-H₂O mixture of compounds **3c** and **3f** are listed in the Supplementary Information (Figures S23 and S24).

Interestingly, the fluorescence emission of derivatives **3b**, **3c**, and **3f** is sensitive to solvent polarity; thus, we aimed to explore their emission behavior in THF as an aprotic water-miscible solvent. The emission responses of compound **3b** upon adding different amounts of water to THF solution is presented in Figure 4. With the increase of water content (0-90% v/v), a great decrease in the emission peak intensities was observed, and the fluorescence intensity as a function of water content showed a slightly bathochromic shift. Tigreros and co-workers previously described similar behavior in a study with pyrazolo derivatives containing a triphenylamine substituent [16]. Thus, the AIE properties were not observed, and this decrease in the emission intensities of derivatives can be directly attributed to an aggregation phenomenon (J- or H-aggregate types) as the water fraction increases. Consequently, this result demonstrates that (trifluoromethyl)pyrazolo-based probes can act as possible fluorescent sensors for small amounts of acid or protic molecules.



Figure 4. (a) Fluorescence emission spectra of compound **3b** and (b) photograph of compound **3b** solutions in THF/water mixture with different water fractions (0–90%) under a UV lamp (365 nm).

3.2.3. Solid-State Analysis—First Evidences

A solid-state absorption and fluorescence emission spectroscopy analysis in powder was performed as the (trifluoromethyl)-pyrazolo derivatives **3a–g** present fluorescence emission in the solid state. The reflectance spectra of the compounds revealed similar absorption peaks compared to the solution study, in which we observed the broadening of the absorption bands (Supplementary Information; Figure S25).

The fluorescence emission data of derivatives **3a–g** in the solid state are listed in Table 2, and all spectra are presented in Figure 5a. Thus, compared to the spectra in solution, the derivatives presented emission peaks very close to the values obtained in organic solvents (Table 1). The variations in emission peaks observed in the solid state can be attributed to a change in the molecular arrangement in the absence of the solvent, which may be favored by π - π stacking interactions. The QY values observed in the solid state for derivatives **3a–g** are smaller than those observed in the solution, which may be directly related to the solid-state arrangement.

Table 2. Photophysical data analysis of derivatives 3a-g in the solid state.

Compound	$\lambda_{abs'}$ nm	λ_{em} nm (QY,%) ^a	SS (nm/cm ⁻¹) ^b	$ au_{\mathrm{f}}$, ns (χ^2) ^c	$k_{ m r}$ (10 ⁸ s ⁻¹) ^d	$k_{ m nr}$ (10 $^{8}~ m s^{-1}$) $^{ m e}$
3a	261, 338, 417	493 (29.0)	76/3700	$3.50 \pm 0.44 \ (1.131901)$	0.83	2.03
3b	286, 338, 425	493 (23.0)	68/3245	3.03 ± 0.59 (1.143012)	0.76	2.55
3c	283, 335, 425	485 (21.0)	60/2910	$8.62 \pm 0.37 \ (1.091558)$	0.24	0.92
3d	294, 340, 427	509 (28.0)	82/3770	$3.00\pm0.45~(1.051683)$	0.93	2.40
3e	290, 428	483 (24.0)	55/2660	$6.62 \pm 0.48 \ (1.131901)$	0.36	1.15
3f	283, 335, 427	542 (29.0)	115/4970	1.36 ± 0.82 (1.151343)	2.13	5.22
3g	268, 331, 433	507 (24.0)	74/3370	$6.14 \pm 0.52 \ (0.919048)$	0.39	1.23

^a Excitation at a less-energy absorption peak using sodium salicylate as standard ($\Phi_f = 55\%$); ^b Stokes shifts: $\Delta \lambda = \lambda_{em} - \lambda_{abs} = 1/\lambda_{abs} - 1/\lambda_{em}$; ^c Using excitation by NanoLED source at 284 nm; ^{d,e} Determined by [23].



Figure 5. Cont.



Figure 5. (a) Normalized steady-state fluorescence emission spectra of compounds **3a–g** in the solid state and (b) normalized fluorescence decay of compounds **3a–g** in the solid state when excited by a NanoLED source at 284 nm.

Compared with the solution study, solid-state fluorescence lifetime measurements were conducted, and lifetime decay plots and the τ_f , radiative (k_r) and non-radiative (k_{nr}) values for derivatives **3a–g** are presented in Figure 5b and Table 2, respectively. It is possible to note a variation in the τ_f values according to the electronic nature of the molecule, which is attributed to the non-influence of the solvent in the excited state and a greater ordering of the molecules in the solid state (Table 2). In addition, we can evidence a decrease in the radiative (k_r) rates with an increase in the non-radiative (k_{nr}) rates, and this is probably evidenced by a relaxation of the vibrational levels of the molecules and restricted motion.

3.3. Thermal Stability in the Solid State

The solid-state thermal stability of compounds 3a-g was accessed using TGA, and the results are summarized in Table 3, where $T_{0.05}$ expresses the temperature at which 5.0% of mass loss occurred and T_d is the temperature of maximum decomposition rate (i.e., the peak of the derivative curve). The order of thermal stability was established in terms of $T_{0.05}$ as follows: **3a** < **3b** < **3d** < **3e** < **3g** < **3c** < **3f**. The TGA curves for compounds **3a**, **3e**, and **3f** are presented in Figure 6, and the other results, including DSC/TGA/DTG curves for compounds **3b** and **3d**, are shown in the Supplementary Information (Figures S26–S33). It is possible to note from Figure 6 and the other curves that the thermal decomposition occurs in a single step with almost 100% of mass loss. Additionally, the values of $T_{0.05}$ are considerably low, especially for compound 3a, indicating low thermal stability for this series of pyrazolo[1,5-*a*]pyrimidines. Regarding $T_{0.05}$ and structure relations, no direct correspondence between molar masses and thermal stability was observed for the entire series. More important than the molar mass of the compounds was the nature of the R substituent. Nonetheless, more detailed explanations for the observed order of thermal stability would require further analysis. From the values of $T_{0.05}$ in Table 3 and the melting temperatures of compounds **3a–g**, it is worth noticing that the majority of the compounds presented considerable mass loss (5%) below their melting point, narrowing possible applications to the solid state.

T _{0.05} (°C)	T _d (°C)	Mass Loss (%)
72	110	99
117	161	97
171	200	99
134	169	96
147	187	97
187	230	99
151	187	98
	T _{0.05} (°C) 72 117 171 134 147 187 151	$\begin{array}{c c} \hline T_{0.05} (^{\circ}C) & T_d (^{\circ}C) \\ \hline 72 & 110 \\ 117 & 161 \\ 171 & 200 \\ 134 & 169 \\ 147 & 187 \\ 187 & 230 \\ 151 & 187 \\ \end{array}$

Table 3. Results of the TGA analysis.



Figure 6. TGA (**a**) and derivative (**b**) curves for compounds **3a** (black line), **3e** (red line), and **3f** (blue line).

4. Conclusions

The synthesis in yields of 50–98% and photophysical behavior of a series of seven examples of 5-(alkyl/aryl/heteroaryl)-substituted 2-methyl-7-(trifluoromethyl)pyrazolo[1,5-a]pyrimidine core (**3**) was achieved, where one new compound (**3**f) was obtained and fully structurally characterized. The optical properties in solution and the solid state of this geminated system **3** were also successfully investigated. In the photophysical evaluation of the molecules, transition bands were observed in the UV region, and moderate to higher values in the quantum fluorescence yields for the derivatives **3a–g**. Regarding the solvent polarity variation, the changes vary according to the electronic nature of the molecules evaluated in the presence or absence of the substituent. Furthermore, photophysical analysis in the solid state and AIE phenomena were also evaluated. For this series of pyrazolo[1,5-*a*]pyrimidines, regarding T_{0.05} and structure relations, no direct correspondence between molar masses and thermal stability was observed for the entire series. Additionally, it is worth noticing that most of the compounds presented considerable mass loss (5%) below their melting point, narrowing possible applications to the solid state.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/photochem2020024/s1. Reference [37] is cited in the supplementary materials.

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