Efficient Microwave Solvent-Free Synthesis of Flavones, Chromones, Coumarins and Dihydrocoumarins

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Abstract: Simple, clean, environmentally friendly procedures for the solvent-free preparation of coumarins, dihydrocoumarins, flavones and chromones under microwave heating are described. Silica-supported Wells-Dawson heteropolyacid ($H_6P_2W_{18}O_{62}\cdot 24\ H_2O$) was employed as catalyst. High selectivity, very good yields and short reaction times were obtained. The results are compared with those of the reactions performed under conventional heating.

Keywords: Acid catalysis, chromones, coumarins, dihydrocoumarins, flavones, microwave, solvent-free, Wells-Dawson heteropolyacid.

INTRODUCTION

Coumarins, dihydrocoumarins, flavones and chromones are important heterocyclic compounds widely distributed in the plant kingdom. They have varied bioactivities and applications in cosmetics, pharmaceuticals, food, flavoring and agrochemicals [1-4]. In consequence, these compounds are very interesting targets to organic chemists, and several strategies for their synthesis have been developed. A very valuable method for the synthesis of coumarins and dihydrocoumarins is the Pechmann reaction, which starts from phenols and β-ketoesters or α,β-unsaturated carboxylic acids [5-8]. The preparation of substituted flavones and chromones is most commonly accomplished by cyclodehydration of 1-(2-hydroxyphenyl)-3-aryl-1,3-diketones [3]. Both reactions involve acidic catalysis, and rough quantities of mineral acid are sometimes required, leading to increased environmental pollution and serious corrosion problems.

Heteropolyacids (HPAs) are useful solid catalysts because of their superacidic properties [9]. As part of a research project to develop environmentally friendly organic reactions, we used the heteropolyacid catalyst $H_6P_2W_{18}O_{62}.24H_2O$ with Wells-Dawson structure in different preparative reactions, under conventional reaction conditions for acylals [10], coumarins [11], benzhydryl ethers [12], flavones and chromones [13], among others.

The increasing demand for clean and "green" chemical synthesis has resulted in increased application of microwave (MW) irradiation as a nonconventional source for the activation of reactions. Microwave-assisted synthesis offers significant advantages over conventional heating, for example, substantial rate enhancements, cleaner formation of products and improvement in yield and selectivity [14-18]. Microwave-assisted reactions under solvent-free conditions provide an opportunity to work with open vessels, thus avoiding the typical problems associated with the use of organic solvent under MW irradiation, such as overpressure and flammability. Furthermore, this approach enhances the possibility of upscaling the reactions [18].

There have been reports about the application of MW irradiation to the synthesis of 4-substituted coumarins [6,19-22], dihydrocoumarins [6,23], flavones and chromones [3,24,25] using different catalysts; however, no report has been made about the use of HPAs.

In this work, a MW-assisted synthesis is presented for substituted coumarins, dihydrocoumarins, flavones and chromones, using silica-supported Wells-Dawson acid as heterogeneous catalyst under solvent-free conditions.

RESULTS AND DISCUSSION

a) Synthesis of Coumarins

We performed the sustainable solvent-free preparation of substituted coumarins from phenols and β-ketoesters or phenylpropiolic acid by the Pechmann reaction (Scheme **1**). Silica-supported Wells-Dawson acid (WD/SiO_2) was tested as catalyst. The employed β-ketoesters were ethyl acetoacetate, ethyl α-methylacetoacetate and ethyl α-fluoroacetoacetate.

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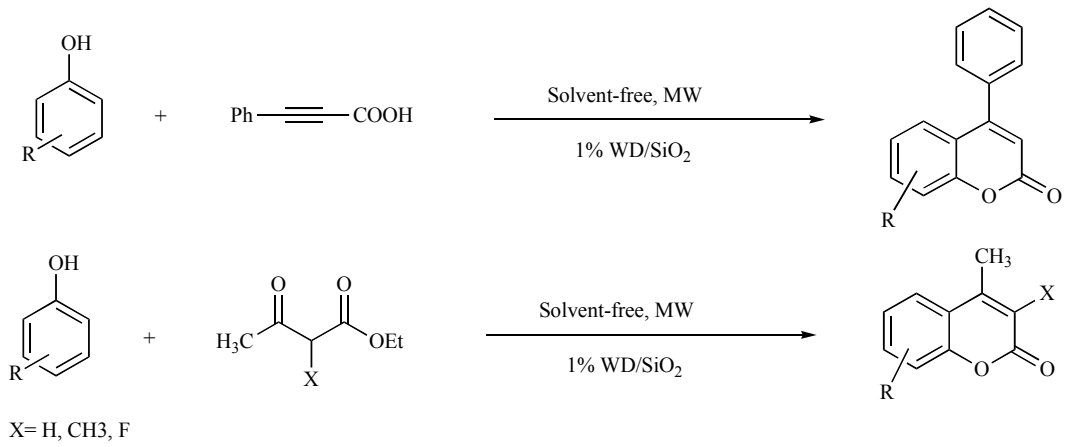
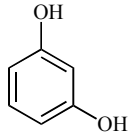
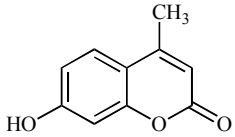
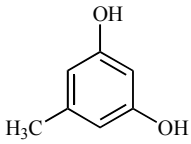
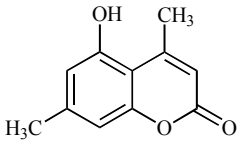
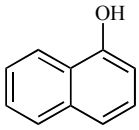
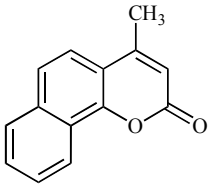
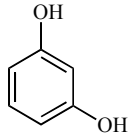
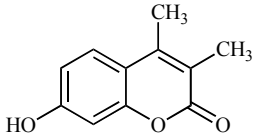
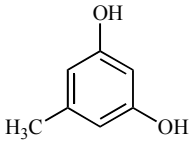
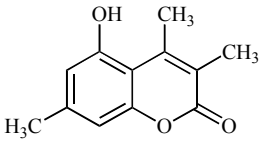
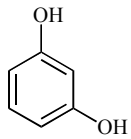
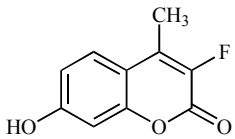
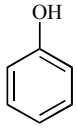
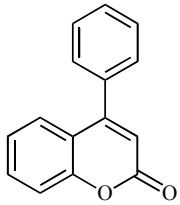
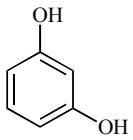
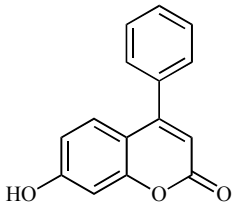
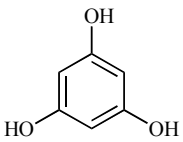
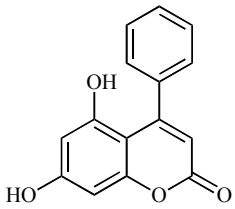


Scheme 1.

Table 1. Preparation of Coumarins Using both Conventional and Microwave Heating

Entry	Phenol	Coumarin	Time (min)[a]	Yield (%)[a]	Time (min)[b]	Yield (%)[b]
1.1			30	87	20	87
1.2			40	86	20	72
1.3			50	75	20	77
1.4			30	87	23	87
1.5			80	74	23	71
1.6			30	90	20	88
1.7					10	99[c]

(Table 1). Contd…..

Entry	Phenol	Coumarin	Time (min)[a]	Yield (%)[a]	Time (min)[b]	Yield (%)[b]
1.8					10	89[c]
1.9					10	54[c]

[a]Conventional heating, 110 °C.
[b]Microwave power: **1**-**6**: 360 w; **7**-**9**: 840 w.
[c]Phenylpropiolic acid was used as starting material.

The experiments were carried out employing both conventional and MW heating, in the presence of 1% mmol catalyst, till consumption of the phenol or until no changes in the composition of the reaction mixture were observed. The obtained results are shown in Table **1**. The optimization of the reaction was performed by checking the temperature, power level, amount of catalyst and phenol:β-ketoester/phenylpropiolic acid molar ratio, using resorcinol as substrate. The use of just 1% mmol WD/SiO_2 is enough to push the reaction forward; higher amounts of catalyst did not improve the results.

In general, high yields of coumarins were attained, almost free of secondary products. The unchanged starting materials were recovered nearly quantitatively. Yields attained by MW irradiation were the same as than those of conventional heating, but the reaction times were considerably shorter. This may be ascribed to a different energy transfer, *via* a dielectric loss in the MW irradiation, while convection/conduction takes place under conventional heating [14-17].

In the case of 4-phenylcoumarins (Table **1**, entries 1.7-1.9), a lower yield was observed when phloroglucinol was employed as substrate (entry 1.9). This could be due to the steric effect of the third hydroxyl.

b) Synthesis of Dihydrocoumarins

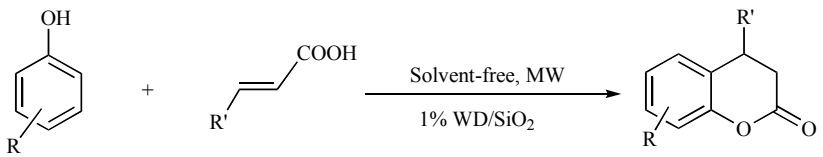
We achieved the sustainable, solvent-free preparation of 3,4-dihydrocoumarins from phenols and α,β-unsaturated carboxylic acids (Scheme **2**) using WD/SiO_2 as catalyst.

In general, good yields of dihydrocoumarins were attained, free of secondary products (Table **2**). The experiments performed under conventional heating gave null or poor results. When MW heating was used, the reaction times were reduced noticeably; however, longer reaction times lowered the yield (Table **2**, entry 2.1). When cinnamic acid reacted with phloroglucinol, the reaction time increased, possibly due to a steric hindrance caused by the third hydroxyl group (entry 2.3). Similarly, the reaction leading to diphenyldihydrocoumarin **2.4** gave the same yield in identical conditions, revealing also the effect of a steric hindrance, perhaps of 3-phenyl group over 4-phenyl group, decreasing the coplanarity between the 4-phenyl group and C4 in the cationic intermediate. Moreover, MW power level showed to be crucial when acrylic acid is used (entry 2.5), at high values (840 w) the yield was poor (38%). This could be, at least partially, because acrylic acid evaporates during that irradiation, condensing in the inner wall of the tube.

c) Synthesis of Flavones and Chromones

We carried out the sustainable, solvent-free synthesis of substituted flavones and 2-arylchromones *via* the cyclization of 1-(2-hydroxyphenyl)-3-aryl-1,3-propanediones (Scheme **3**) using WD/SiO_2 as catalyst.

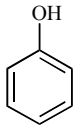
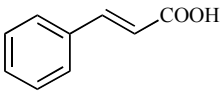
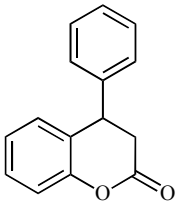
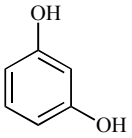
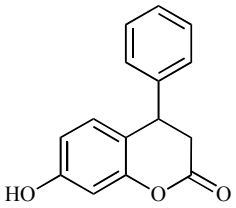
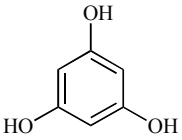
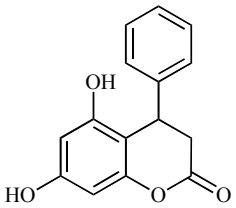
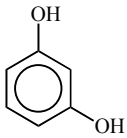
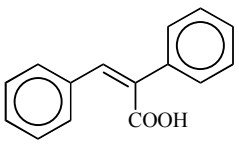
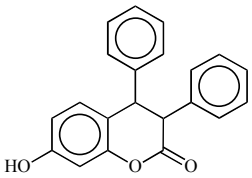
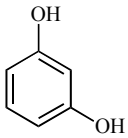
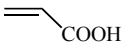
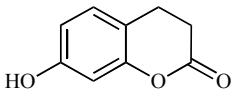
All the experiments were performed under conventional and MW heating, in the presence of 1% mmol catalyst. The results are summarized in Table **3**. Temperature, power level and molar ratio of WD/SiO_2 to substrates were checked in order to establish the optimum reaction conditions, using 1-(2-hydroxyphenyl)-3-phenyl-1,3-propanedione as substrate.



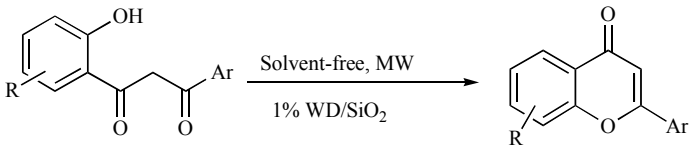
R' = H, Ar

Scheme 2.

Table 2. Preparation of Dihydrocoumarins (2.1-5)

Entry	Phenol	Acid	Dihydrocoumarin	Time (min.)	Power (w)	Yield (%)
2.1				5 10 120[a]	960 960	60 40 44[a]
2.2				7 270[a]	840	68 0[a]
2.3				15	840	56
2.4		trans 		15	840	56
2.5				15	120	82

[a]Conventional heating, 110 °C.



Scheme 3.

The use of just 1% mmol of catalyst is enough to push the reaction forward; higher amounts of the catalyst did not improve the results. The experiments were run until 1,3-diketone was consumed or until no changes in the composition of the reaction mixture were observed.

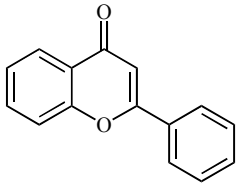
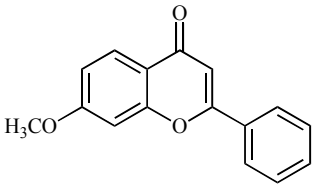
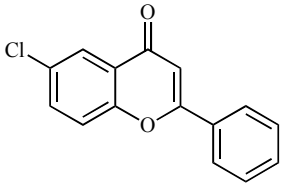
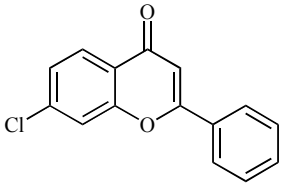
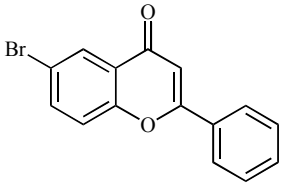
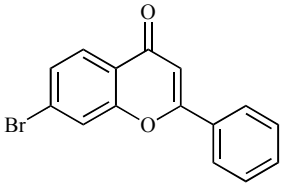
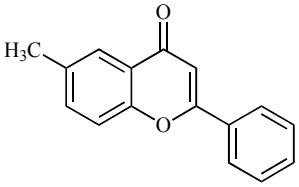
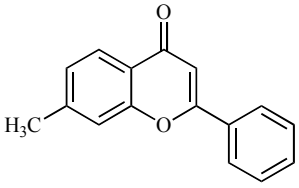
In all cases the desired products were obtained with high selectivity, and almost free of secondary products. The unchanged starting materials were recovered nearly quantitatively. Recycling of the catalyst (Table **3**, entries 3.1 and 3.9) was checked in two consecutive batches after the first one; the catalyst showed almost constant activity. The heating using MW irradiation led not only to an important decrease in the reaction time, as expected, but also, in most of the cases, to a slight increase in the reaction yield, showing that MW irradiation contributes to the cleanliness of the reaction. Moreover, no stereoelectronic effects of the substituent on the yield for each type of heating were observed.

CONCLUSION

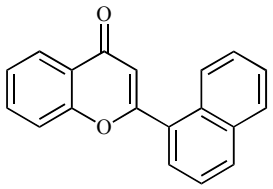
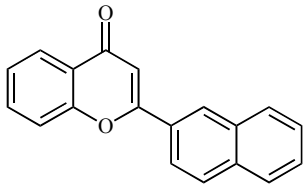
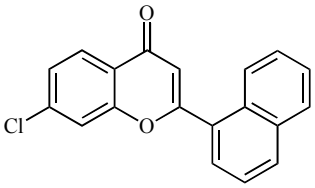
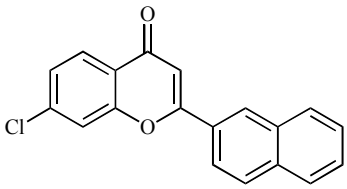
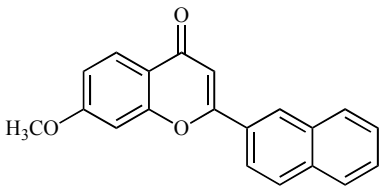
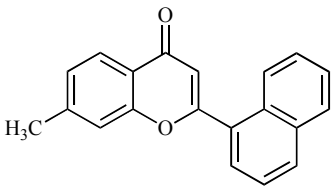
The described procedures provide clean, fast, and useful alternatives for the solvent-free, microwave-assisted synthesis of coumarins, dihydrocoumarins, flavones and arylchromones.

The use of MW irradiation as the power source and supported WD acid as catalyst affords good to excellent yields

Table 3. Preparation of Flavones and Chromones Using Conventional and Microwave Heating

Entry	Flavone/Chromone	Time (min)[a]	Yield (%)[a]	Time (min)[b]	Yield (%)[b]
3.1		30	87	5	88(86,87)[c]
3.2		30	83	5	90
3.3		40	87	7	96
3.4		30	86	5	93
3.5		35	87	7	92
3.6		35	85	7	91
3.7		30	86	5	89
3.8		30	86	5	88

(Table 3). Contd…..

Entry	Flavone/Chromone	Time (min)[a]	Yield (%)[a]	Time (min)[b]	Yield (%)[b]
3.9		40	87	8	92(90,89)[c]
3.10		40	88	8	91
3.11		50	85	7	95
3.12		35	84	5	90
3.13		40	83	7	88
3.14		40	85	7	82

[a]Conventional heating, 110 °C.
[b]Microwave power: 840 w.
[c]Yields obtained in the first and second reusing of the catalyst.

of products in low reaction times. The advantages of the procedures are the low formation of wastes and the replacement of corrosive mineral acids. Furthermore, the use of a heterogeneous catalyst allows its easy separation and recovering. The filtered catalyst is ready for its immediate reutilization, with no activity decrease being noted. The catalyst is easy to prepare, the low cost, and no toxicity was registred for this heteropolyacids.

EXPERIMENTAL

General Procedures and Statements

Microwave experiments were carried out in a domestic MW oven (2450 MHz). All the reactions were monitored by TLC on precoated silica gel plates (254 μm). Flash column chromatography was performed with 230-400 mesh silica gel. All the yields were calculated from crystallized products. All the products were identified by comparison of physical data (mp, TLC, NMR) with those reported or with those of authentic samples prepared by the respective conventional methods using sulfuric acid as catalyst. Melting points of the compounds were determined in sealed capillary tubes and are uncorrected. ^{13}C NMR and ^{1}H NMR spectra were recorded at room temperature on Bruker AC-250 and Bruker Avance DPX-400 spectrometers using TMS as internal standard. Elemental microanalyses were performed in F & M instrument. Entries and target compounds have the same number.

A simple household microwave oven equipped (Global Home) with a turntable was used for microwave heating (2450 MHz) at full power. The nominal (output) power indicated in the equipment is 1000 W.

General Procedure for Preparing 1,3 Diketones

All the starting 1,3-diketones were prepared following a procedure described elsewhere [26]. 2-Acetylphenyl naphthoate (1 mmol) or 2-acetylphenylbenzoate (1mmol) dissolved in pyridine (1.8 ml) was warmed at 50 °C. Fresh crushed dry KOH (1.5 mmol) was added and the suspension was further stirred by 15 min, and then acidified with HCl 4M. The solid was filtered, washed and dried, and purified by recrystallization.

Catalyst Preparation

Silica-supported Wells-Dawson acid (WD/SiO_2) was prepared by wet impregnation of Grace Davison silica (Grade 59, specific area= 250 m^2/g) with an aqueous solution of Wells-Dawson (WD) acid (synthesized by the Drechsel method [27]). A catalyst containing 10 wt% of WD acid was obtained (1 g HPA/10 g silica). After impregnation, samples were dried at room temperature in a vacuum desiccator for 8 h.

Procedures for Preparing Coumarins

A) Conventional Heating

A mixture of phenol (1 mmol), ethyl acetoacetate or phenylpropiolic acid (1 mmol) and WD/SiO_2 catalyst (1% mmol) was charged in an open glass tube (20 ml) and stirred at 110°C for the indicated time (see Table **1**). When the reaction time was over, the reaction mixture was extracted with hot toluene (3x2 ml). The solution was concentrated in vacuum, and the crude product was recrystallized from methanol or ethanol. Alternatively, the catalyst was extracted wich water (3x5 ml) and the crude product was recristalyzed from methanol o ethanol.

B) Microwave Heating

A mixture of the same composition as in Procedure A was placed in an open glass tube and was irradiated for the time and power level given in Table **1**. At the end of the exposure to MW irradiation, the isolation and purification of products were accomplished as described in Procedure A.

7-Hydroxy-4-methylcoumarin (**1.1**): mp: 186-188 °C (methanol) (lit. mp: 185-187 °C); [28] ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.23 (d, 3H, J= 1.0 Hz), 5.97 (d, 1H, J= 1.1 Hz), 6.57 (d, 1H, J= 2.3 Hz), 6.70 (dd, 1H, J= 2.3, 8.8 Hz), 7.44 (d, 1H, J= 8.8 Hz), 10.55 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 18.9, 103.1, 110.8, 113.2, 114.1, 127.5, 155.0, 155.4, 161.7, 162.6.

5-Hydroxy-4,7-dimethylcoumarin (**1.2**): mp: 249-251 °C (methanol) (lit. mp: 248 °C); [5] ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.28 (s, 3H), 2.54 (s, 3H), 6.05 (s, 1H), 6.58 (s, 1H), 6.62 (s, 1H), 10.5 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 21.0, 23.4, 106.5, 107.0, 107.6, 111.9, 142.7, 154.5, 154.8, 156.4, 159.7.

7,8-Benzo-4-methylcoumarin (**1.3**): mp: 155-156 °C (ethanol) (lit. mp: 153-154 °C); [29] ^{1}H NMR (400 MHz, DMSO-d_6) δ 2.56 (d, 3H, J= 1.1 Hz), 6.53 (d, 1H, J= 1.2 Hz), 7.72-7.75 (m, 2H), 7.83 (d, 1H, J= 8.8 Hz), 7.90 (d, 1H, J= 8.8 Hz), 8.06-8.08 (m, 1H), 8.38-8.41 (m, 1H).

7-Hydroxy- 3,4-dimethylcoumarin (**1.4**): mp: 255-256 °C (methanol) (lit. mp: 256 °C); [30] ^{1}H NMR (250 MHz, DMSO-d_6) δ 2.02 (s, 3H), 2.29 (s, 3H), 6.65 (d, 1H, J= 2.1 Hz), 6.75 (dd, 1H, J= 2.1, 8.5 Hz), 7.54 (d, 1H, J= 8.5 Hz), 10.35 (s, 1H). ^{13}C NMR (62.5 MHz, DMSO-d_6) δ 12.5, 14.5, 101.7, 112.3, 112.5, 116.7, 125.9, 146.6, 152.9, 159.8, 161.1.

5-Hydroxy-3,4,7-trimethylcoumarin (**1.5**): mp: 249-251 °C (methanol) (lit. mp: 249 °C); [31] ^{1}H NMR (250 MHz, DMSO-d_6) δ 2.02 (s, 3H), 2.25 (s, 3H), 2.50 (s, 3H), 6.55 (s, 2H), 10.30 (s,1H). ^{13}C NMR (62.5 MHz, DMSO-d_6) δ 12.5, 18.8, 20.7, 106.8, 107.3, 111.9, 117.9, 140.8, 148.0, 152.9, 155.5, 160.6.

3-Fluoro-7-hydroxy-4-methylcoumarin (**1.6**): mp: 233-234 °C (methanol) (lit.: no data); ^{1}H NMR (250 MHz, DMSO-d_6) δ 2.25 (d, 3H, J= 3.0 Hz), 6.67 (d, 1H, J= 2.4 Hz), 6.79 (dd, 1H, J= 2.4, 8.8 Hz), 7.49 (d, 1H, J= 8.8 Hz), 10.4 (s, 1H). ^{13}C NMR (62.5 MHz, DMSO-d_6) δ 10.5 (d, J= 3.9 Hz), 102.9, 111.6 (d, J= 2.3 Hz), 114.2, 127.1 (d, J= 5.4 Hz), 132.6 (d, J= 13.0 Hz), 144.3, 152.1 (d, J= 2.3 Hz), 155.0, 160.9. Anal Calcd. For $C_{10}H_7FO_2$: C 67.42, H 3.96; Found: C 67.40, H 3.93.

4-Phenylcoumarin (**1.7**): mp: 102-104 ºC (methanol) (lit. mp: 105 ºC); [23] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.42 (s, 1H), 7.20 (dd, 2H, J= 2.5, 8 Hz), 7.33 (m, 5H), 7.50 (dd, 2H, J= 2.5, 8 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 106.0, 121.3, 125.1, 126.1, 126.2, 126.6, 127.5, 127.8, 128.1, 135.0, 148.0, 159.2, 162.1.

7-Hydroxy-4-phenylcoumarin (**1.8**): mp: 238-240 ºC (methanol) (lit. mp: 240 ºC); [32] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.42 (s, 1H), 6.70 (dd, 2H, J= 2.5, 8 Hz), 7.46 (d, 1H, J= 8 Hz), 7.50-7.62 (m, 5H), 7.89 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 105.0, 105.7, 112.4, 120.3, 126.0, 127.4, 127.8, 128.1, 135.2, 151.3, 158.6, 158.9, 162.0.

5,7-Dihydroxy-4-phenylcoumarin (**1.9**): mp: 250-251 ºC (methanol) (lit. mp: 252ºC); [32] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.43 (s, 1H), 6.50 (s, 1H), 7.40 (s, 1H), 7.41-7.58 (m, 5H), 7.85 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 99.5, 100.9, 105.9, 114.3, 126.2, 127.5, 128.0, 134.9, 152.0, 157.0, 159.0, 159.1, 161.9.

Procedures for Preparing Dihydrocoumarins

A) Conventional Heating

A mixture of phenol (1 mmol), cinnamic acid or acrylic acid (1 mmol) and WD/SiO_2 catalyst (1% mmol) was charged in an open glass tube (20 ml) and stirred at 130°C for the indicated time (see Table **2**). After the reaction time was over, the reaction mixture was extracted with dichloromethane (5 ml). The extract was washed with H_2O; then it was dried with anhydrous sodium sulfate and filtered. Evaporation of the solvent under reduced pressure and recrystallization from hexane gave the pure product.

B) Microwave Heating

The same mixture used in Procedure A was placed in an open glass tube and exposed to MW irradiation for the indicated time and power level (see Table **2**). The isolation and purification of products was performed as described in Procedure A.

4-Phenyl-3,4-dihydrocoumarin (**2.1**): mp: 78-79 ºC (methanol) (lit. mp: 80-82 ºC); [23] ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.13 (dd, 2H, J= 6, 16 Hz), 4.37 (t, 1H, J= 6 Hz), 6.99 (d, 1H, J= 8 Hz), 7.01 (d, 1H, J= 8 Hz), 7.08-7.14 (m, 1H), 7.15-7.21 (m, 2H), 7.26-7.41 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 37.1, 40.7, 125.3, 125.5, 125.8, 126.8, 127.5, 129.8, 130.4, 143.3, 148.6, 167.7.

7-Hydroxy-4-phenyl-3,4-dihydrocoumarin (**2.2**)**:.** mp: 141-142 ºC (methanol) (lit. mp: 140-142 ºC); [23] ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.06 (dd, 2H, J= 6, 16 Hz), 4.39 (t, 1H, J= 6 Hz), 6.61-6.65 (m, 2H), 6.89 (d, 1H, J= 8 Hz), 7.20-7.37 (m, 5H), 8.78 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 38.2, 41.0, 104.8, 112.5, 118.1, 127.2, 127.5, 29.8, 130.4, 143.3, 150.0, 159.0, 168.3.

5,7-Dihydroxy-4-phenyl-3,4-dihydrocoumarin (**2.3**): mp: 208-210 ºC (methanol) (lit. mp: 211 ºC); [33] ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.06 (dd, 2H, J= 6 , 16 Hz), 4.45 (t, 1H, J= 6 Hz), 6.24 (s, 1H), 6.30 (s, 1H), 7.26-7.41 (m, 5H), 8.75 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 26.5, 41.0, 97.3, 99.7, 115.7, 127.4, 129.9, 130.4, 143.2, 151.4, 156.1, 160.2, 168.0.

7-Hydroxy-3,4-diphenyl-3,4-dihydrocoumarin (**2.4**): mp: ~300 ºC (methanol) (lit.: no data); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.41 (d, 1H, J= 6 Hz), 5.07 (d, 1H, J= 6 Hz), 6.87 (m, 2H), 6.90 (d, 1H, J= 8 Hz), 7.10-7.55 (m, 10H), 8.70 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 41.2, 51.5, 125.0, 125.4, 125.5, 125.6, 126.7, 127.5, 127.7, 129.0, 129.7, 129.8, 130.5, 131.7, 135.2, 143.0, 148.8, 169.3. Anal Calcd. For $C_{21}H_{16}O_3$: C 79.73, H 5.10; Found: C 79.74, H 5.12.

7-Hydroxy-3,4-dihydrocoumarin (**2.5**): mp: 132-133 ºC (methanol) (lit. mp: 133-134 ºC); [6] ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.88 (m, 4H), 6.15 (s, 2H), 6,62 (d, 1H, J= 8 Hz), 7,9 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.2, 25.2, 104.2, 111.9, 115.4, 126.7, 149.5, 158.8, 168.2.

Procedures for Preparing Flavones and Chromones

A) Conventional Heating

A mixture of 1-(2-hydroxyphenyl)-3-aryl-1,3-diketone (0.5 mmol) and WD/SiO_2 catalyst (1% mmol) was charged in an open glass tube (20 ml) and stirred at 110°C for the indicated time (see Table **3**). When the reaction time was over, the reaction mixture was extracted with hot toluene (3x2 ml). The solution was washed with NaOH 3M and H_2O; then it was dried with anhydrous sodium sulfate, filtered and concentrated in vacuum. The solid crude product was recrystallized from methanol or hexanes. Alternatively, the catalyst was extracted wich water (3x5 ml) and the crude product was recristalyzed from methanol or hexanes.

B) Microwave Heating

The same mixture used in Procedure A was charged in an open glass tube and subjected to MW irradiation at 840 w for the specified period given in Table **3**. The isolation and purification of products were accomplished as indicated in Procedure A.

Flavone (**3.1**): mp: 96-97 °C (methanol) (lit. mp: 98 °C); [34] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.82 (s, 1H), 7.41 (ddd, 1H, J= 1.0, 7.2, 8.2 Hz), 7.49-7.56 (m, 4H), 7.68 (ddd, 1H, J= 1.7, 7.2, 8.3 Hz), 7.92-7.95 (m, 2H), 8.23 (dd, 1H, J= 1.8, 8.2 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 107.3, 117.9, 123.7, 124.9, 125.5, 126.0, 129.0, 131.5, 131.8, 133.5, 155.9, 163.1, 177.9.

7-Methoxyflavone (**3.2**): mp: 111-112 °C (methanol) (lit. mp: 110 °C); [35] ^{1}H NMR (400 MHz, DMSO-d_6) δ 3.92 (s, 3H), 6.97 (s, 1H), 7.07 (dd, 1H, J= 2.4, 8.8 Hz), 7.32 (d, 1H, J= 2.4 Hz), 7.58-7.60 (m, 3H), 7.94 (d, 1H, J= 8.8 Hz), 8.05-8.12 (m, 2H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 56.3, 101.1, 106.9, 114.9, 117.3, 126.3, 126.4, 129.3, 131.3, 131.8, 157.7, 162.3, 164.1, 176.6.

6-Chloroflavone (**3.3**): mp: 184-185 °C (methanol) (lit. mp: 183-184 °C); [37] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.84 (s, 1H), 7.54-7.56 (m, 4H), 7.65 (dd, 1H, J= 2.5, 8.8 Hz), 7.91-7.94 (m, 2H), 8.20 (d, 1H, J= 2.6 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 107.5, 119.9, 125.0, 125.2, 126.3, 129.1, 131.2, 131.4, 131.9, 134.0, 154.5, 163.6, 177.2.

7-Chloroflavone (**3.4**): mp: 156-157 °C (methanol) (lit. mp: 156-157 °C); [36] ^{1}H NMR (250 MHz, $CDCl_3$) δ 6.82 (s, 1H), 7.42 (dd, 1H, J= 1.9, 8.4 Hz), 7.52-7.55 (m, 3H), 7.61 (d, 1H, J= 1.9 Hz), 7.90-7.93 (m, 2H), 8.22 (d, 1H, J= 8.4 Hz). ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 107.2, 118.2, 122.4, 126.0, 126.3, 126.8, 129.0, 131.3, 131.7, 139.6, 156.0, 163.2, 177.9.

6-Bromoflavone (**3.5**): mp: 189-190 °C (methanol) (lit. mp: 189-190 °C); [38] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.82 (s, 1H), 7.52-7.55 (m, 4H), 7.83 (dd, 1H, J= 2.4, 8.3 Hz), 7.89-7.92 (m, 2H), 8.35 (d, 1H, J= 2.4 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 107.5, 119.5, 119.9, 125.1, 126.3, 128.1, 129.1, 131.1, 131.9, 136.2, 154.6, 163.8, 178.0.

7-Bromoflavone (**3.6**): mp: 164-165 °C (methanol) (lit. mp: 167-168 °C); [36] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.85 (s, 1H), 7.53-7.57 (m, 3H), 7.62 (dd, 1H, J= 1.5, 8.2 Hz), 7.80 (d, 1H, J= 1.5 Hz), 7.91-7.94 (m, 2H), 8.18 (d, 1H, J= 8.2 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 107.5, 121.1, 122.4, 126.0, 126.4, 128.1, 128.6, 128.9, 131.3, 131.5, 155.3, 163.5, 177.0.

6-Methylflavone (**3.7**): mp: 122-123 °C (methanol) (lit. mp: 122-123 °C); [40] ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.47 (s, 3H), 6.82 (s, 1H), 7.46-7.54 (m, 5H), 7.92-7.94 (m, 2H), 8.02 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.9, 107.3, 117.7, 123.5, 124.9, 126.2, 128.9, 131.4, 131.8, 134.9, 135.1, 154.4, 163.1, 178.5.

7-Methylflavone (**3.8**): mp: 121-122 °C (methanol) (lit. mp: 120 °C); [39] ^{1}H NMR (250 MHz, $CDCl_3$) δ 2.45 (s, 3H), 6.75 (s, 1H), 7.20 (d, 1H, J= 9.9 Hz), 7.30 (s, 1H), 7.40-7.55 (m, 3H), 7.91-7.97 (m, 2H), 8.10 (d, 1H, J= 9.9 Hz). ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 22.0, 107.5, 118.0, 122.0, 126.0, 126.8, 127.2, 129.0, 131.7, 132.0, 145.1, 156.3, 163.2, 178.2.

2-(1-Naphthyl)chromone (**3.9**): mp: 142-143 °C (methanol) (lit. mp: 138-139 °C); [35] ^{1}H RMN ($CDCl_3$, 400 MHz): δ 6.72 (s, 1H), 7.49 (dt, 1H, J= 0.9, 7.6 Hz), 7.55-7.63 (m, 4H), 7.74 (dt, 1H, J= 1.8, 7.8 Hz), 7.79 (dd, 1H, J= 1.2, 7.2

Hz), 7.96-7.99 (m, 1H), 8.05 (d, 1H, J= 8.3 Hz), 8.15-8.18 (m, 1H), 8.34 (dd, 1H, J= 1.5, 7.9 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 113.1, 118.2, 124.0, 124.8, 125.0, 125.3, 125.8, 126.6, 127.4, 127.9, 128.7, 130.3, 130.7, 131.5, 133.7, 133.8, 156.7, 165.4, 178.2.

2-(2-Naphthyl)chromone (**3.10**): mp: 164-165 °C (methanol) (lit. mp: 164-165 °C); [35] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.94 (s, 1H), 7.43 (ddd, 1H, J= 1.6, 6.6, 7.9 Hz), 7.54-7.60 (m, 2H), 7.63 (d, 1H, J= 8.0 Hz), 7.72 (ddd, 1H, J= 1.6, 6.6, 7.9 Hz), 7.87-8.05 (m, 4H), 8.23 (dd, 1H, J= 1.5, 7.9 Hz), 8.46 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 107.9, 118.1, 122.3, 124.0, 125.2, 125.7, 126.7, 126.9, 127.6, 128.0, 128.7, 128.7, 129.1, 132.9, 133.8, 134.5, 156.3, 163.4, 178.3.

7-Chloro-2-(1-naphthyl)chromone (**3.11**): mp: 196-197 °C (methanol) (lit. mp: 198-199 °C); [41] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.70 (s, 1H), 7.46 (dd, 1H, J= 1.9, 8.5 Hz), 7.58-7.63 (m, 4H), 7.78 (dd, 1H, J= 1.1, 7.2 Hz), 7.97-7.99 (m, 1H), 8.06 (d, 1H, J= 8.2 Hz), 8.12-8.14 (m, 1H), 8.26 (d, 1H, J= 8.6 Hz). ^{13}C NMR (100 MHz, $CDCl_3$) δ 113.3, 118.3, 122.5, 124.7, 125.1, 126.2, 126.7, 127.2, 127.6, 128.0, 128.8, 130.2, 130.3, 131.7, 133.7, 139.9, 156.8, 165.6, 177.4.

7-Chloro-2-(2-naphthyl)chromone (**3.12**): mp: 219-220 °C (hexanes) (lit.: no data); ^{1}H RMN ($CDCl_3$, 250 MHz): δ 6.93 (s, 1H), 7.39 (dd, 1H, J= 2.0, 8.6 Hz), 7.55-7.63 (m, 2H), 7.66 (d, 1H, J= 2.0 Hz), 7.86-7.98 (m, 4H), 8.18 (d, 1H, J= 8.6 Hz), 8.45 (s, 1H). ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 108.1, 118.2, 122.4, 122.7, 126.1, 127.0, 127.2, 127.2, 127.9, 128.2, 128.7, 129.1, 129.1, 133.0, 134.8, 139.8, 156.5, 163.5, 177.4. Anal Calcd. For $C_{19}H_{11}ClO_2$: C 74.40, H 3.61; Found: C 74.39, H 3.61.

7-Methoxy-2-(2-naphthyl)chromone (**3.13**): mp: 181-182 °C (methanol) (lit. mp: 182-183 °C); [26] ^{1}H NMR (400 MHz, DMSO-d_6) δ 3.91 (s, 3H), 6.85 (s, 1H), 6.94 (dd, 1H, J= 1.7, 8.9 Hz), 6.99 (d, 1H, J= 1.5 Hz), 7.49-7.60 (m, 2H), 7.82-8.00 (m, 4H), 8.11 (d, 1H, J= 8.9 Hz), 8.39 (s, 1H). ^{13}C NMR (100 MHz, DMSO-d_6) δ 55.9, 100.4, 107.9, 114.4, 117.8, 122.3, 126.5, 126.9, 126.9, 127.7, 127.7, 128.7, 128.7, 128.8, 132.9, 134.5, 158.1, 162.9, 164.3, 177.7.

7-Methyl-2-(1-naphthyl)chromone (**3.14**): mp: 161-162 °C (methanol) (lit. mp: 162-163 °C);[13] ^{1}H NMR (250 MHz, $CDCl_3$) δ 2.50 (s, 3H), 6.65 (s, 1H), 7.27 (d, 1H, J= 9.3 Hz), 7.32 (s, 1H), 7.54-7.60 (m, 3H), 7.75 (dd, 1H, J= 0.8, 6.7 Hz), 7.92-7.96 (m, 1H), 8.01 (d, 1H, J= 8.3 Hz), 8.11-8.15 (m, 1H), 8.18 (d, 1H, J= 8.1 Hz). ^{13}C NMR (62.5 MHz, $CDCl_3$) δ 21.8, 113.0, 118.0, 121.9, 124.9, 125.0, 125.6, 126.5, 126.8, 127.3, 127.8, 128.7, 130.5, 130.9, 131.4, 133.8, 145.2, 156.9, 165.1, 178.1.

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