SYNTHESIS OF 2,4,6,8,10,12-HEXABENZYL-2,4,6,12-HEXAAZATETRACYCLO DODECANE USING MELAMINIUM TRI(HYDROGENSULFATE) AS A SOLID ACID CATALYST

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Abstract

In this article, the authors successfully synthesized 2,4,6,8,10,12-hexabenzyl-2,4,6,12-hexaazatetracyclo dodecane (HBIW) through a condensation reaction using melaminium tri(hydrogensulfate) as a solid acid catalyst. The structural characteristics of the product were determined using modern analytical methods: IR, DSC, NMR, and HPLC. Factors influencing the yield of the HBIW synthesis reaction were examined, including catalysts and catalyst amount. The results show that using melaminium tri(hydrogensulfate) as a solid catalyst at 10% mol of glyoxal, yields an optimal yield of 89.86%.

Keywords: *HBIW; condensation reaction; melaminium tri(hydrogensulfate).*

1. Introduction

The hexanitrohexaazaisowurtzitan (HNIW, commonly known as CL-20), is a multi-ring nitroamine high energy of explosive with the chemical formula $C_6H_6N_{12}O_{12}$ (Fig. 1) [1]-[3]. CL-20 can store and release large amounts of chemical energy rapidly on demand, having important military and civilian applications [4]-[6]. In 1987, CL-20 was first developed by the China Lake facility in California, USA, primarily for use in propellants. CL-20 is considered to have a better oxidizer-fuel ratio than conventional HMX (octogen) or RDX (hexogen), which can release 20% more energy than traditional HMX-based propellants [7]-[9]. It significantly outperforms conventional high-energy explosives and propellants. As a result, the development and application of this compound as a high-energy fuel for bombs, ammunition, and rocket propellants is attracting attention from scientists and military forces worldwide. During the development process, CL-20 was handled by Thiokol Corporation, and the U.S. [10]. The Navy has also shown interest in using CL-20 for missile propellants. The use of this compound has characteristics that improve missile camouflage by reducing the visibility of smoke emissions. The evolution of defense technology has a direct association with developing new high-energy materials that are superior in their energy-mass and performance characteristics to the existing ones [11].

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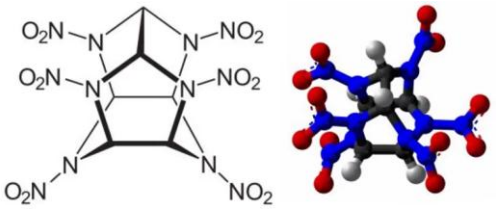

Fig. 1. The HNIW of chemical formula.

The first step in HNIW (CL-20) synthesis involves creation of the basic cage structure through condensation of glyoxal with benzylamine, leading to the formation of 2,4,6,8,10,12-hexabenzyl-2,4,6,12-hexaazatetracyclo dodecane, commonly referred to as hexabenzylhexaaza - isowurtzitane (HBIW) [12]-[15]. Conversion of HBIW to CL-20 poses a major challenge. Direct nitration of HBIW to CL-20 by nitrolysis is unsuccessful because of competing nitration of phenylrings and thereby necessitates debenzylation by catalytic hydrogenation prior to nitration [16], [17]. The lack of understanding of the formation mechanisms of hexaazaisowurtzitane derivative CL-20 precursors is a barrier to solving the said problems [18]. HBIW is a key compound in the process of synthesizing the explosive material CL-20 (Fig. 2).

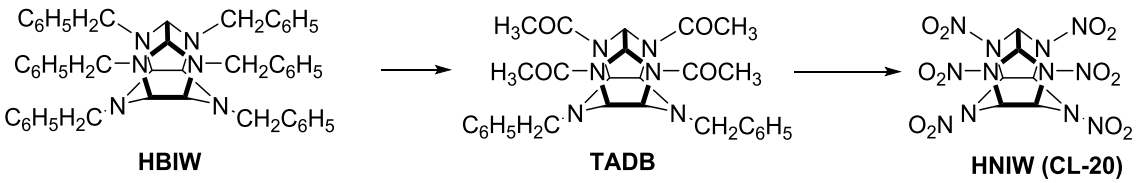

Fig. 2. Synthesize CL-20 method.

Recently ionic liquids (ILs) have gained significant attention as suitable media in various of chemistry [19]-[21]. Among ionic liquids, Brønsted acidic ionic liquids have been reported as promising catalysts for acid catalyzed reactions and play a dual role in a variety of synthetic reactions as solvent and catalyst. Fortunately, the authors found out the solid catalyst melaminium-tris(hydrogen sulfate) (called MTS), which acts as an acid for the condensation reaction of benzylamine and glyoxal in the synthesis of HBIW. In this study, the authors focused on the utilization of acidic ionic liquids as an environmentally attractive media to develop a new one-pot methodology for the synthesis of HBIW and a simple and convenient method for synthesis: effective, mild conditions, purification easy and high yield of product.

2. Experiment

2.1. Chemicals and equipment

Reagents were purchased from commercial suppliers and used as received. The solvents used were freshly distilled under anhydrous conditions, unless otherwise

specified. All the reactions have been monitored by thin layer chromatography (TLC), carried out on 0.25 mm Merk silica gel plates (60 F_{254}). Catalytic reactions were carried out in Schlenk flasks under N_2 atmosphere using pre-dried glassware. Flash chromatography was performed with 300-400 mesh silica gel. Visualization of the developed chromatogram was performed by fluorescence quenching, ceric ammonium molybdate, or potassium permanganate staining solution. The yields reported were for isolated, spectroscopically pure compounds. The melting point was determined based on the differential scanning calorimetry (DSC) curve measured with a Pyris Diamond Perkin Elmer Differential Scanning Calorimeter; the Fourier-transform infrared spectroscopy (FTIR) has been recorded with Spectrum Two spectrometer at Le Quy Don Technical University. The nuclear magnetic resonance (NMR) spectra have been recorded with Brucker Avance 500 spectrometers at Vietnam National University; HPLC Shimadzu system, Agilent C18 4.6 × 250 mm column, flow rate: 1 mL/min, solvent as 5% acetonitrile (ACN) - 95% phosphoric acid 0.1%, Detection wavelength: 254 nm, at the National Institute of Medicinal Materials. ^{1}H NMR (500 MHz) spectra: δ (H) are given in ppm relative to tetramethylsilane (TMS), using [δ ($CDCl_3$) = 7.26 ppm; δ (DMSO-d_6) = 2.49 ppm] as internal reference. ^{13}C NMR (125MHz) spectra: δ (C) are given in ppm relative to TMS, using [δ ($CDCl_3$) = 77.0 ppm; δ (DMSO-d_6) = 39.50 ppm] as internal reference.

2.2. Synthesis of MTS

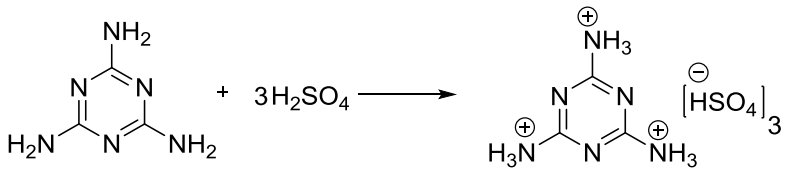

Fig. 3. Synthesis of MTS.

A 50 mL flask charged with sulfuric acid 98% (1.4 mL, 25.5 mmol) was put into an ice-bath, and melamine (3.8 g, 9.2 mmol) was added in portions over a period of 10 min. The resulting mixture was stirred for 30 min. Afterwards $CHCl_3$ (15 mL) was added to it, and stirred for 10 min. The resulting solid was filtered, washed with $CHCl_3$, and dried to give MTS as a white solid. The product of structure was determined by FT-IR spectrum, a characteristic peak for the -OH functional group of the acid wider pick appears at a position of 3385 cm^{-1}. The peaks at 1625, 1526, 1465, and 1431 cm^{-1}

are characteristic of the aromatic ring vibrations of melamine. From this, it can be concluded that the structure of the product is MTS, a salt of melamine and sulfuric acid.

2.3. HBIW synthesis procedure

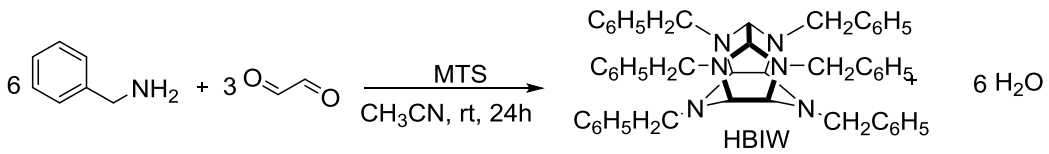

Fig. 4. Synthesis of HBIW.

To a 100 mL round-bottom flask with a stir bar, added 6 mL benzylamine, 5 mL distilled water, 1.88 g (4 mmol) MTS acid, and 50 mL acetonitrile. The mixture was stirred and cooled in an ice bath, obtaining a homogeneous transparent solution. Slowly add 2.9 mL of 40% glyoxal to the flask over 10 minutes. Rinse the glyoxal container with 1 mL distilled water and add it to the reaction system. After adding glyoxal, the reaction system was brought to room temperature and allowed to react for 16-18 hours, yielding a yellow-white solid precipitate. At the end of the reaction, the precipitate was filtered and washed several times with cold acetonitrile, obtaining 5.3 g of white solid product with a yield of 89.86%. Crystallization from acetonitrile yielded white needle-like crystals.

3. Results and discussion

3.1. Product analysis

3.1.1. FT-IR, NMR spectra analysis of HBIW

The results of the FT-IR, ^{1}H-NMR, and ^{13}C-NMR spectra of HBIW are shown in Figs. 5-7, respectively.

The structural characteristics of HBIW were identified using FT-IR spectroscopy (Fig. 5). The FT-IR spectrum showed several characteristic peaks corresponding to the vibrations of various functional groups in the HBIW molecule. Notably, there is no appearance of vibrations for N-H bonds (3700-3000 cm^{-1}) and C=O (1850-1640 cm^{-1}), but the spectrum does show vibrations at the following wave numbers: 3061, 2835 (CH, s), 1601 (C=C), 1492-1450 (CH_2 bend), 1349-1168 (C-C), 1120-985 (C-N), 698 (C-H bend).

The ^{1}H-NMR spectrum (Fig. 6) showed signals at δ (ppm) = 7.23 (m, 30H, phenyl), δ = 4.10 (m, 12H, CH_2), δ = 3.58 (s, 6H, CH), and there was no signal at around δ ≈ 1.5 ppm for the proton in the -NH_2 group (from the benzylamine molecule) or δ ≈ 5.0 ppm for the proton in the -CH=O group (from the glyoxal molecule).

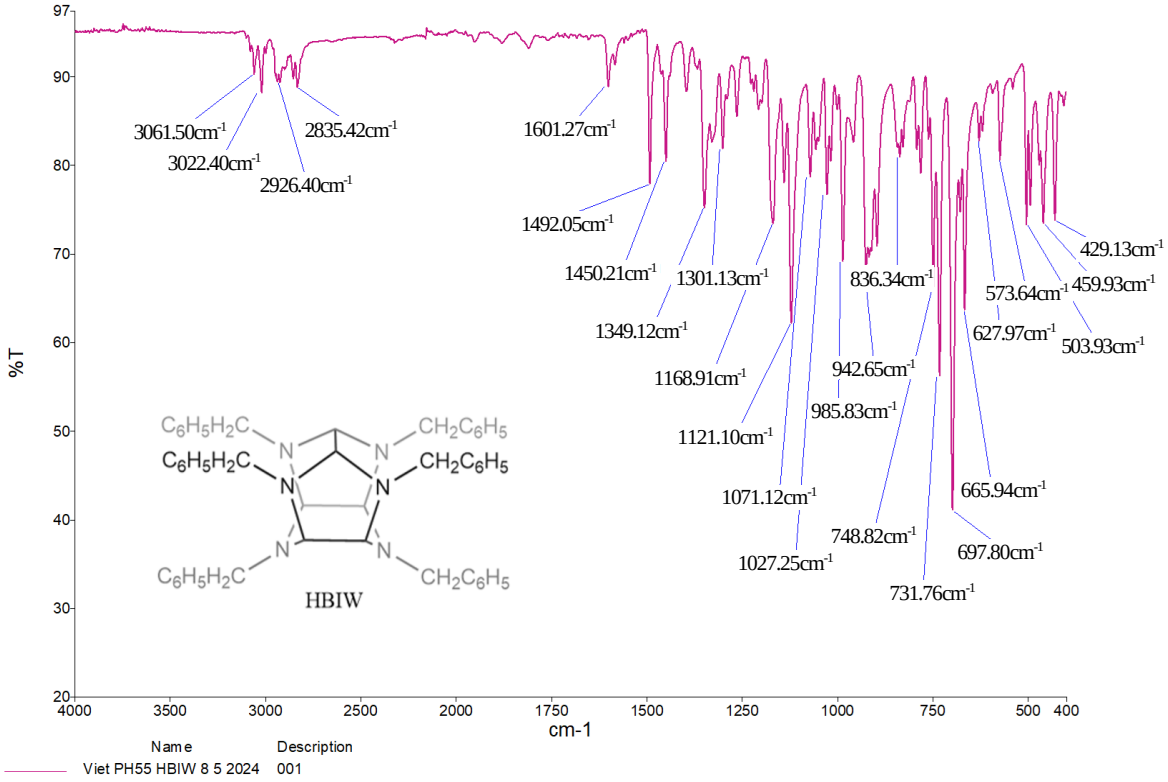

Fig. 5. FT-IR Spectrum of HBIW.

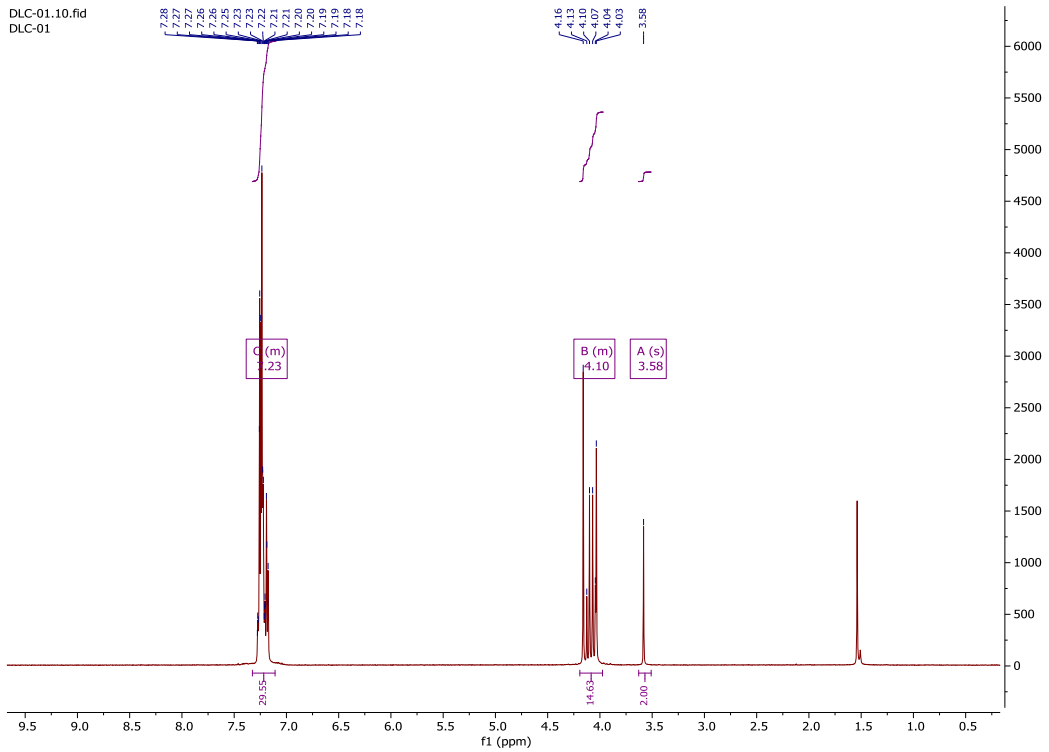

Fig. 6. ^{1}H-NMR Spectrum of HBIW.

The ^{13}C-NMR spectrum (Fig. 7) confirmed the presence of 48 carbon atoms with δ (ppm) = 56.23-56.89 (6C, CH_2 from the benzyl group), δ = 80.68 (6C, CH from the cage structure), δ = 126.62-140.75 (36C, phenyl). Based on the FT-IR, NMR spectra, and the melting temperature data, and comparing with published studies [24], it can be concluded that the cage structure of the HBIW molecule has been successfully synthesized.

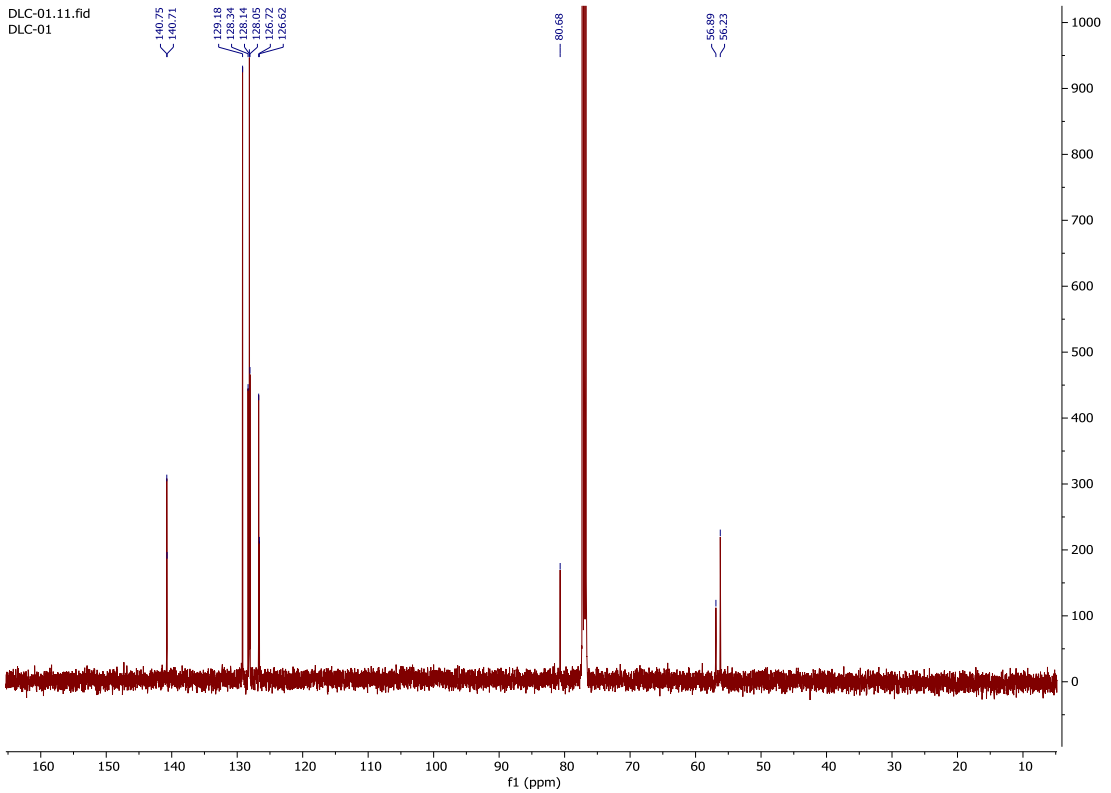

Fig. 7. ^{13}C-NMR Spectrum of HBIW.

3.1.2. DSC analysis

The results of the melting temperature of the product are shown through the DSC curve (Fig. 8). From the shape of the DSC curve, which shows a narrow, sharp, and symmetrical peak with a straight baseline, the melting temperature of the product was determined to be in the range of 152.02-155.17°C, indicating high purity. Based on previous published studies [22], [23] on the melting temperature of HBIW, it is observed that the melting temperature of the synthesized HBIW samples is consistent with those reported in the literature.

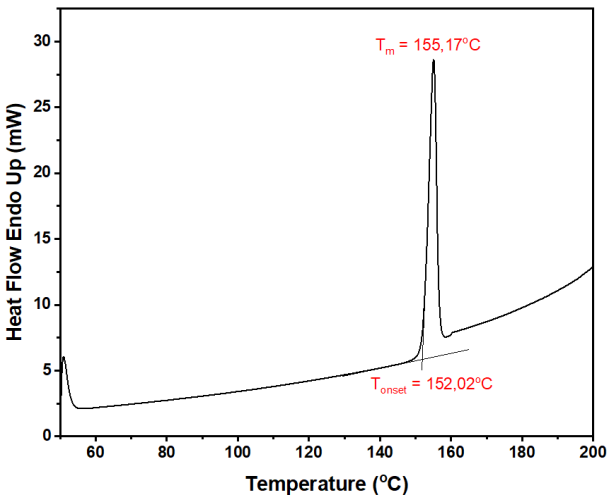

Fig. 8. DSC Curve of the HBIW Sample.

3.1.3. HPLC spectra analysis of HBIW

The product of purity was determined by HPLC, HBIW was dissolved into a vessel which contained 25 mL of a mixture of methanol-water (v/v, 60:40). Acetonitrile/1%-Phosphoric (v/v, 5:95) as flow phase. The purity of HBIW is 97.76% (Fig. 9).

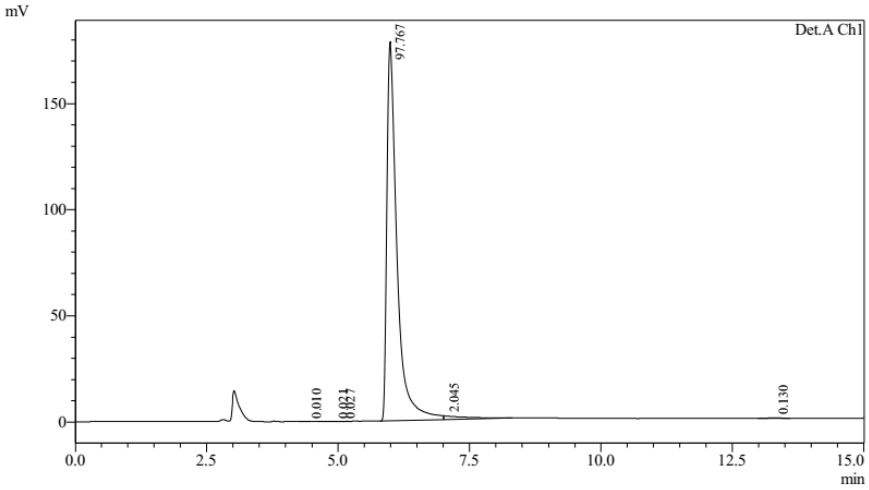

Fig. 9. HPLC spectra of HBIW.

3.2. Effect of catalysts on reaction efficiency

Firstly, the authors investigated the effect of different acid catalysts on the synthesis efficiency of HBIW. The results of the investigation are shown in Tab. 1. From the results in Tab. 1, the reaction yield for synthesizing HBIW depends on the acid catalyst used. Without the catalyst, the reaction proceeds slowly, and the product is yellow gum in lower yield than with the catalyst. In the presence of H^+ ions, the

carbonyl group of glyoxal becomes protonated, making it a stronger electrophile, which increases its reactivity to the nucleophile (the -NH_2 group of benzylamine), promoting the formation and stabilization of the imine intermediate and facilitating the formation of the HBIW cage structure. When HCl, H_2SO_4, HNO_3 are added to the reaction system under cooling, white fumes are observed on the solution surface due to the strong evaporation of the concentrated acids. However, no such phenomenon occurs with acetic acid, which is soluble in the solvent and less acidic, thus providing a milder reaction. The authors were investigating some Lewis acid catalysts; however, the reaction did not occur, with only $ZnCl_2$ giving a low yield of 3.57%. The authors' experimental findings suggest that organic acids are more effective as catalysts than strong inorganic acids, likely because strong acids may cause side reactions or excessive catalysis, hindering the formation of HBIW. Fortunately, for the solid catalyst MTS (Tab. 1), it exhibited excellent yield.

Tab. 1. Effect of catalyst on HBIW synthesis efficiency

Entry	**Catalyst**	**Yield (%)**
1	-	-
2	Formic acid	80.13
3	Acetic acid	59.55
4	Hydrochloric acid	52.68
5	Sulfuric acid	43.52
6	Nitric acid	49.24
8	Trisodium citrate dihydrate	27.12
9	Diammonium oxalate monohydrate	30.17
10	Acid citric monohydrate	-
11	$ZnCl_2$	3.57
12	$FeCl_2$	-
13	$CuFeCl_2$	-
14	**MTS**	81.96

Reaction conditions: Benzylamine (0.0085 mol, 0.937 mL), glyoxal (0.0037 mol, 0.427 mL), CH_3CN (7.75 mL), H_2O (0.775 mL), and catalyst (5% mol glyoxal). Reactions carried out in 24 hours under nitrogen atmosphere at room temperature.

Formic acid and MTS acid both provide high yields; however, after the reaction, the product purified with MTS catalyst is simpler and achieves the highest yield. To

maintain the required H^+ concentration, the authors chose MTS solid acid as the catalyst because it gave the highest yield.

3.3. Effect of MTS acid catalyst amount on reaction efficiency

To study the effect of the MTS acid catalyst on the product yield, experiments were conducted using different amounts of catalyst. The experimental results are shown in Tab. 2.

From the results in Tab. 2, it is evident that the product yield increases as the amount of MTS acid catalysts rises to 20% mol of glyoxal. However, when the MTS acid amount exceeds 10%, the yield decreases. This suggests that excess MTS acid may begin to hinder the reaction by promoting side reactions, destabilizing intermediates, or affecting the stability of reactants, which reduces the overall reaction yield. Therefore, the authors chose 10% mol of solid acid MTS as the optimal catalyst for subsequent investigations.

Tab. 2. Effect of formic acid catalyst amount on HBIW synthesis efficiency

Entry	Catalyst (% mol)	Yield (%)
1	3	58.41
2	5	81.96
3	10	89.86
4	15	71.84
5	20	61.53

Reaction Conditions: Benzylamine (0.0085 mol, 0.937 mL), glyoxal (0.0037 mol, 0.427 mL), CH_3CN (7.75 mL), H_2O (0.775 mL), and MTS (x% mol glyoxal). Reactions carried out in 24 hours under nitrogen atmosphere at room temperature.

4. Conclusion

The authors have successfully synthesized the MTS catalyst for the synthesis of HBIW, with high performance, easy isolation, and simple product formation. Structural characteristics were verified using FT-IR, NMR, DSC, and HPLC. The study on factors affecting HBIW synthesis efficiency showed that using MTS acid as a solid catalyst (10% mol relative to glyoxal), acetonitrile as a solvent, and stirring for 24 hours resulted in the highest yield of 89.86%. With further optimization of reaction conditions, HBIW is fully suitable for use in subsequent stages of CL-20 production at a large scale, contributing to the development of defense technologies and enhancing future weapons capabilities.

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TỔNG HỢP 2,4,6,8,10,12-HEXABENZYL-2,4,6,12-HEXAAZATETRACYCLO DODECANE SỬ DỤNG XÚC TÁC AXIT RẮN MELAMINIUM TRI(HYDROGENSULFATE)

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Tóm tắt: Trong nghiên cứu này, tiền chất HBIW được tổng hợp thành công từ phản ứng ngưng tụ sử dụng xúc tác axit rắn MTS. Cấu trúc sản phẩm được xác định bằng các phương pháp phân tích hiện đại: IR, DSC, NMR, HPLC. Các yếu tố ảnh hưởng tới hiệu suất phản ứng tổng hợp HBIW được khảo sát bao gồm: chất xúc tác, lượng chất xúc tác. Sản phẩm phản ứng sử dụng chất xúc tác axit MTS với lượng 10% số mol glyoxal, thực hiện trong dung môi acetonitrile trong 24 giờ thu được hiệu suất tối ưu là 89,86%.

Từ khóa*: HBIW; phản ứng ngưng tụ; MTS - melaminium tri(hydrogensulfate).*

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