Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 35-42, 4, 2024
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Araştırma Makalesi

https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 35-42, 4, 2024
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Research Article

Optimization of Urea Formaldehyde Resin Production: Understanding Chemical Reaction Kinetics and Process Parameters

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(Received:09 April 2024, Accepted: 15 May 2024)

(2nd International Conference on Scientific and Innovative Studies ICSIS 2024, April 18-19, 2024)

ATIF/REFERENCE: Karataş, M., Erzen, B., Deniz, Ş., & Aydoğmuş, E. (2024). Optimization of Urea Formaldehyde Resin Production: Understanding Chemical Reaction Kinetics and Process Parameters. *International Journal of Advanced Natural Sciences and Engineering Researches*, 8(4), 35-42.

Abstract – The synthesis of urea formaldehyde resin (UFR) involves a condensation reaction between urea and formaldehyde, typically carried out in an aqueous solution. The urea/formaldehyde molar ratio is a very important factor affecting the properties of the resulting resin and these ratios vary between 1/1 and 1/1.5. Higher formaldehyde contents cause resins to have better water resistance but also lead to increased brittleness of the polymer. The chemical reaction is catalyzed by acidic or basic conditions, and acidic catalysts such as sulfuric acid or hydrochloric acid are commonly used. This reaction proceeds by adding formaldehyde to the amine groups of urea, leading to the formation of methylene bridges between urea molecules. The reaction is exothermic and temperature plays a crucial role in controlling the rate and extent of resin formation. In this study, the chemical reaction takes place at temperatures between 70 °C and 90 °C. According to the results obtained, it is determined that as the formaldehyde/urea molar ratio increases, bulk density, Shore D hardness, and thermal conductivity coefficient rise. Additionally, experimental studies have been carried out at atmospheric pressure. Optimization of process parameters, including temperature, pressure, catalyst concentration, and reaction time, is often accomplished using experimental design methodologies to maximize resin yield and desired properties while minimizing production costs. This comprehensive evaluation of chemical reaction kinetics and process parameters has been performed. Urea is crucial for the efficient and cost-effective production of formaldehyde resins and has implications for a wide range of industrial applications.

Keywords – Urea Formaldehyde, Reaction Kinetics, Process Optimization, Production Parameters, Characterization

I. INTRODUCTION

Phenolic resins are polymeric compounds that have been used for millennia and are still being developed today. They are significant ingredients for thermosetting resins. A polymer is a material made up of huge molecules, or macromolecules, that are made up of several subunits that repeat [1]. These resins are created when an aldehyde, such as formaldehyde, reacts with phenol, or any other phenolic component. Through cross-linking, this process produces a thermoset structure. Because of this, phenolic resins are resistant to harsh chemicals and temperatures. Phenolic resins therefore play a significant role in the polymer sector. The creation of composite materials is a significant application for phenolic resins. They are widely utilized, particularly in sectors of the economy where mechanical and thermal durability are essential. Additionally, they are favored in several applications, including coatings, adhesives, and insulating materials [2].

The four primary categories of materials in the polymer group include fibers, plastics, elastomers, and engineered rubber. Thermoplastics and thermosets are the two sub-branches of plastics, and natural and synthetic rubbers are the two sub-branches of elastomers [3]. Thermosetting polymers with substantial commercial value fall into one of the following categories: urea formaldehyde, phenol-formaldehyde, melamine formaldehyde, epoxy, and unsaturated polyester resins [4]. Urea-formaldehyde is a commercially significant amino resin that is part of the aminoplast family of resins [5].

The primary ingredient of UFR, urea, is created by reacting ammonia and carbon dioxide to form crystalline, tiny, spherical particles that are colorless to the naked eye and readily soluble in water. The condensation result of urea and formaldehyde is urea-formaldehyde glue [6]. Although UFR contains only two monomers (urea and formaldehyde), the interaction between them is extremely complex due to their high reactivity [7]. The interaction between urea and formaldehyde occurs through acid condensation and alkaline methylolation [8]. The chemical reaction mechanism in the synthesis of UFR is expressed in Figure 1 [9].

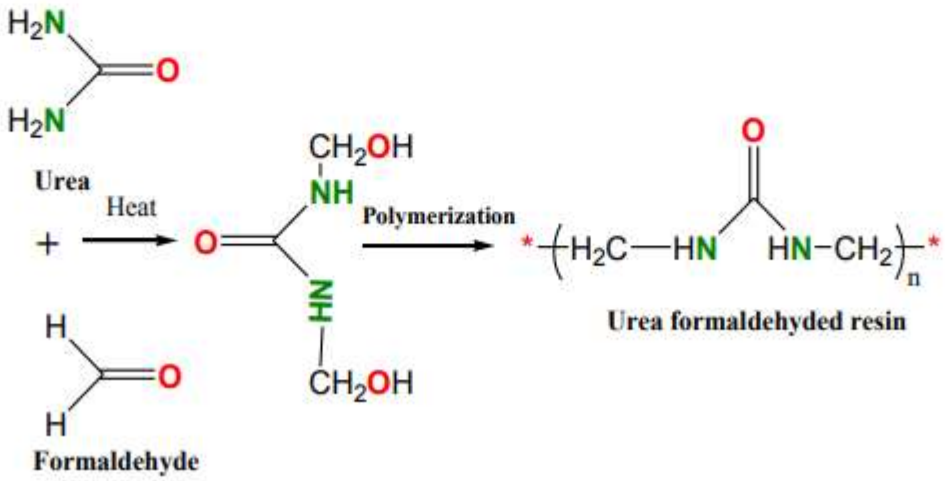

Figure 1. Chemical reaction steps in the synthesis of UFR

Since urea-formaldehyde resins are inexpensive, highly reactive, and have excellent adherence to wood, they are frequently employed in the production of wooden goods. In addition to these, it is known to be utilized in several industries, including the pharmaceutical, leather, ceramics, anti-corrosion, and insulating foam sectors [10]. Urea-formaldehyde resins have several benefits over other adhesives, including not flammability, good adhesion, compatibility with a variety of hardening conditions, high reactivity, complete hardening, good thermal properties, odorless, and low cost [11].

UFRs are produced using various synthesis methods. These methods include alkaline catalysis, acidic catalysis, emulsion polymerization, and solution polymerization. Researchers determine the optimum synthesis conditions by examining the effects of different synthesis methods on the properties and performance of resins [12].

UFRs are used in many areas, from the furniture industry to the automotive industry, from adhesives and coatings to the textile and paper industry. Studies in the literature evaluate the performance and properties of such resins in different application areas according to their usage areas. The performance of UFR depends on factors such as durability, adhesion properties, and chemical and thermal stability [13].

UFR may raise significant environmental and health concerns. For this reason, there are many studies in the literature on the environmental effects, emissions, and health risks of resins. These studies contribute to the establishment of policies and regulations regarding the production, use, and disposal of resins [14].

UFR is a versatile resin widely used in various industries due to its physical and chemical properties such as adhesion and water resistance. UFR is widely used as a bonding agent in the production of engineered wood products such as particleboard, medium-density fiberboard, plywood, and laminated veneer lumber. It improves the structural integrity and dimensional stability of the final product by creating a strong bond between wood particles or fibers. UFR is used as a wrinkle-resistant agent for cotton fabrics in textile processes. It is applied to fabrics to provide wrinkle resistance, hardness, and shape retention. UFR is used as a wet-strength additive in paper and cardboard production. UFR-treated paper, packaging materials, banknotes, and special papers are made, which increases the paper's durability and printability by increasing its resistance to tearing, wrinkling, and moisture. UFR is used in the production of insulation materials such as fiberglass insulation sheets and foam insulation panels. It acts as a binder that holds insulation fibers or particles together and provides thermal and acoustic insulation properties to building materials. UFR resin is used in the production of automotive components such as interior trim, door panels, and headliners. It contributes to the lightweight structure and structural integrity of automotive parts by acting as an adhesive in bonding various materials such as plastic, fabric, and foam. UFR is also used as a coating agent for controlled-release fertilizers and slow-release nitrogen fertilizers in agricultural applications. Encapsulating fertilizers prevents the leakage of nutrients and extends the fertility and life of fertilizers in the soil [15-19].

The production of UFR occurs via a one-step polymerization between urea and formaldehyde under alkaline conditions. Formaldehyde is usually prepared by oxidation of methanol in the presence of a catalyst such as silver or copper. This step produces formaldehyde gas, which dissolves in water to form formalin, the solution containing approximately 37% formaldehyde. Urea is dissolved in water and methanol is added to the solution to control the reaction rate and reduce viscosity. To initiate the reaction, the mixture is heated to a certain temperature. Formaldehyde is added to the urea-methanol mixture under alkaline conditions (NaOH). Formaldehyde reacts with urea to form methylene bridges between urea molecules, resulting in a three-dimensional polymer network. This process continues until the desired degree of polymerization is achieved. The resin is then cured at high temperatures to promote cross-linking and further polymerization, leading to the formation of a solid, thermosetting polymer. After curing, the pH of the resin is adjusted to a neutral or slightly acidic range to stabilize the product and remove unreacted formaldehyde or acidic byproducts. UFR uses additives such as fillers, plasticizers, and stabilizers to improve its properties [20,21].

In this study, some physical and chemical properties of urea formaldehyde resin (UFR) have been examined. The effect of formaldehyde/urea molar ratios on the bulk density, Shore D hardness, and thermal conductivity coefficient of UFR are evaluated. Additionally, the chemical reaction mechanism of UFR and optimization of experimental conditions are also determined.

II. MATERIAL AND METHOD

Materials used in experiments

The urea and formaldehyde components used in this study were supplied by Polisan Kimya. Gloves, protective glasses, laboratory coats, pipettes, beakers, heated magnetic stirrers, and thermometers are used in experimental studies.

The method used in experiments

Necessary consumables and equipment are prepared under laboratory conditions. A precision scale is used to take the necessary measurements. After the necessary calculations are made, certain amounts of components are taken into the beaker and mixed. Attention should also be paid to the mixing order, operating temperature, and duration. After the resulting resin reaches a gel consistency, it is cast into standard molds. After the curing process is completed, the necessary physical and characterization procedures are carried out [22]. In Figure 2, the production scheme of UFR is generally expressed.

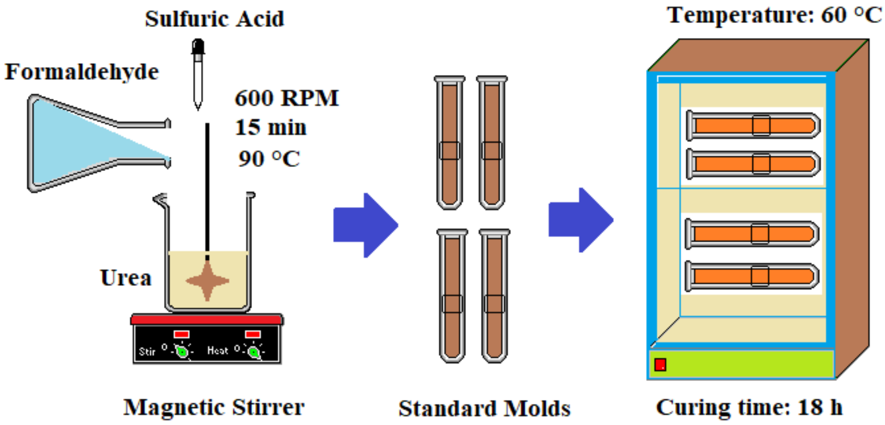

Figure 2. Production scheme of UFR

Bulk density of UFR

The mass of the examined UFR sample is determined using a precision balance. The volume of UFR is calculated using cylindrical standard molds. A digital caliper is used to check whether there is a decrease in volume after curing. Bulk density is calculated from the mass/volume ratio of UFR. The result found is converted to kg/m^3 in g/cm^3 [23].

Shore D hardness of UFR

Shore D hardness testing is a widely used method to measure the surface hardness of polymeric materials. This test is performed by applying a predetermined load to the surface of the polymer. The smooth surface of UFR is prepared and cleaned for the test. A force perpendicular to the surface is applied with the Shore D hardness tester. It is ensured that the device probe is in full contact with the sample surface. The readings on the device (Shore Hardness Tester LX-D-2) are recorded, measurements are repeated three times, and the average is taken [24].

Thermal conductivity coefficient of UFR

Thermtest TLS-100 is a thermal conductivity measuring device used to measure the coefficient of thermal conductivity. UFR, which has a homogeneous structure, is prepared for measurement by removing it from the standard mold. The sample to be measured is placed in the sampling section of the device. For example, full contact with the device is ensured and measurements are repeated three times. The results are interpreted in the graph drawn by taking the average of the results [25].

Fourier transform infrared (FTIR) analysis of UFR

FTIR analysis of UFR has been performed with Shimadzu IRSpirit QATR-S device. In FTIR analysis, sample preparation, determination of analysis parameters, sample analysis, data processing, and evaluation of the results are carried out respectively. In this study, the spectra of the UFR sample are scanned in the wavelength range of 400 to 4000 cm^{-1} [26].

III. RESULTS AND DISCUSSION

According to the results obtained in experimental studies, the bulk density, Shore D hardness, and thermal conductivity coefficient of UFR have been examined. In Figure 3, the bulk density of UFR is expressed according to the formaldehyde/urea molar ratio. It is understood that as this ratio rises, the bulk density of UFR increases.

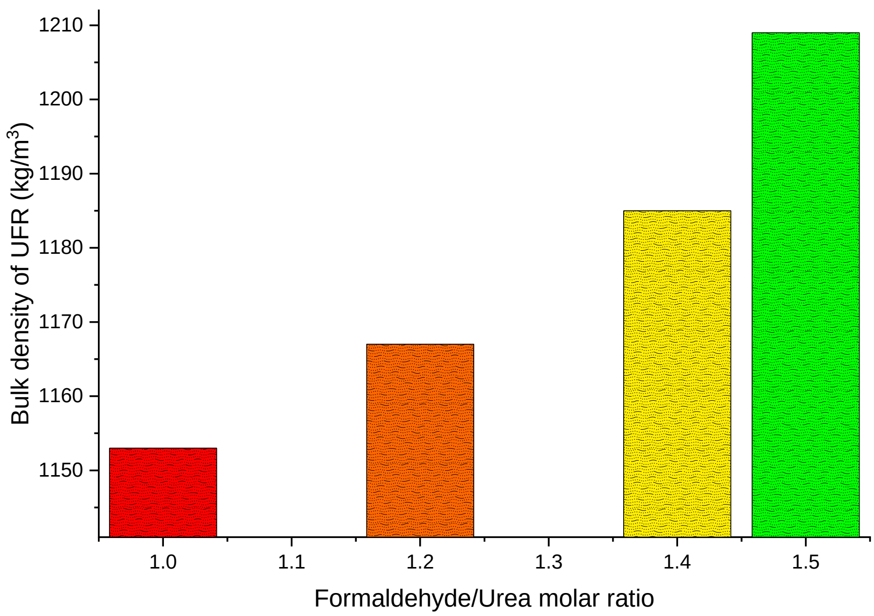

Figure 3. Variation of bulk density with formaldehyde/urea molar ratio

Figure 4 shows that as the formaldehyde/urea molar ratio increases, Shore D hardness of UFR rises. Besides, it is understood from Figure 5 that as this ratio increases, the thermal conductivity coefficient also rises.

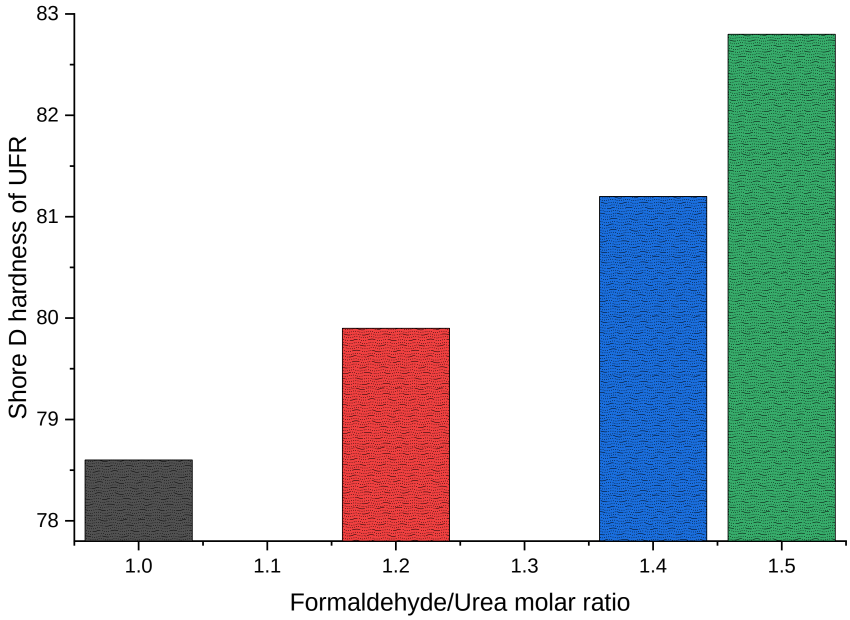

Figure 4. Variation of hardness with formaldehyde/urea molar ratio

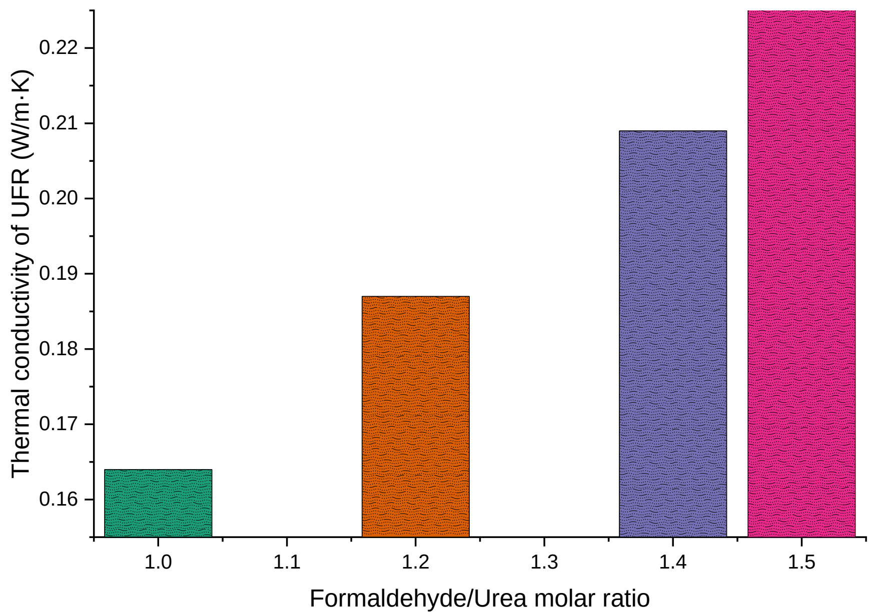

Figure 5. Variation of thermal conductivity coefficient with formaldehyde/urea molar ratio

FTIR spectra of UFR

Functional groups in FTIR spectra of urea formaldehyde; are listed as carbonyl group (C=O) from urea and formaldehyde, amide group ($CONH_2$) from urea, methylene group (CH_2) from formaldehyde, and hydroxyl group (OH) from formaldehyde. The carbonyl group (C=O) in urea and formaldehyde appears in the wavelength range of 1675-1740 cm^{-1}. The amide group of urea creates the (N-H) stretching peak in the wavelength range of 3300-3400 cm^{-1}. The C=O stretching peak shows its peak in the wavelength range of 1600-1650 cm^{-1}. The methylene group (CH_2) in formaldehyde creates the C-H stretching peak at a wavelength of 2850-295 cm^{-1}. The hydroxyl group in formaldehyde creates the hydroxyl stretching peak around 3350-3550 cm^{-1}. The intensity and shape of the absorption peaks in FTIR spectra provide information about the abundance and environment of functional groups in the molecule. Strong and sharp peaks indicate high concentrations of specific functional groups. Broad peaks may indicate interactions between different functional groups or the presence of hydrogen bonds [27,28]. In this study, FTIR spectra of urea formaldehyde provide valuable information about the molecular structure, functional groups, and chemical composition of the resin (Figure 6).

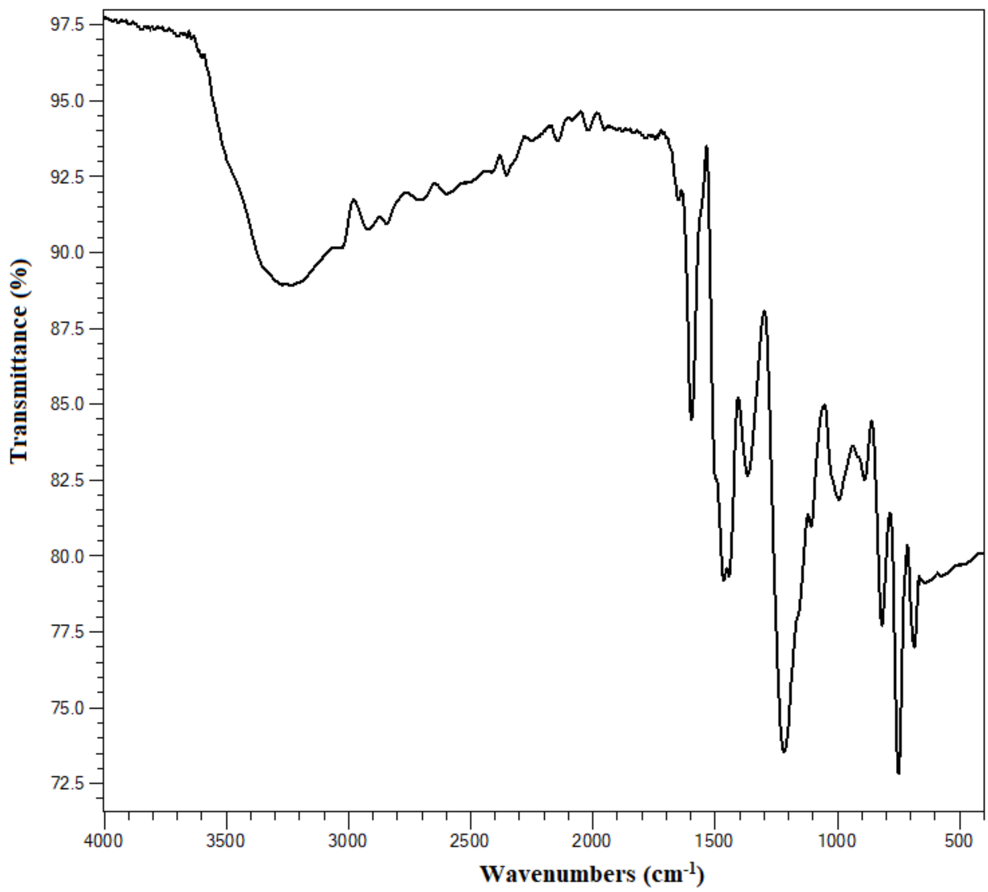

Figure 6. FTIR spectra of UFR

CONCLUSIONS

The synthesis of urea-formaldehyde resins is a complex chemical process involving the condensation reaction between urea and formaldehyde under certain conditions. Urea/formaldehyde molar ratio, catalytic conditions, temperature, and reaction time play critical roles in determining the properties of the resulting resin.

It is stated that the urea/formaldehyde molar ratio affects some physical and chemical properties of the resin. Although higher formaldehyde content increases surface hardness, it causes brittleness. Therefore, it is very important to use components in optimum proportions for the purpose.

In this study, sulfuric acid is preferred to catalyze the condensation reaction. The chemical reaction proceeds by adding formaldehyde to the amine groups of urea, creating methylene bridges between urea molecules. Resin formation and rate can be controlled by temperature. Chemical reactions generally occur faster at higher temperatures.

Experimental studies are carried out at temperatures between 70 °C and 90 °C for resin formation under atmospheric pressure conditions. According to the results obtained, optimum efficient production is achieved at 90 °C and with urea/formaldehyde molar ratio (1/1.2). Besides, it is understood that as the formaldehyde/urea molar ratio increases, bulk density, Shore D hardness, and thermal conductivity coefficient rise.

Overall, urea plays a crucial role in facilitating the efficient and cost-effective production of formaldehyde resins with implications for various industrial applications. Evaluation of chemical reaction kinetics and process parameters in this context provides valuable information for resin synthesis in industrial environments. Research in this area is expanding into improving reaction conditions, investigating alternative catalysts, and the environmental and health effects of urea-formaldehyde resin production.

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