



Project Summary



An Evaluation of Pristine Lignin for Hazardous Waste Treatment

Daniel J. O'Neil, Christopher J. Newman, E. S. K. Chian, and H. Gao

A feasibility study was conducted to assess the utilization of lignin, isolated from a steam-exploded hardwood (Tulip poplar) with 95% ethanol and 0.1N NaOH, as a potential adsorbent for hazardous waste treatment. Eight organic compounds and two heavy metals were selected to allow comparison of lignin isolates with activated carbon.

Adsorption kinetic studies, adsorption size studies, and adsorption isotherms based on the Freundlich equation were completed. The lignin isolates were extensively characterized using instrumental and classical wet techniques.

It was found that the adsorption capacity of lignin for heavy metals (chromium and lead) is comparable to activated carbon, despite a huge divergence in surface area (0.1 m²/g vs. 1000 m²/g). The surface area discrepancy and the extensive aromatic substitution in lignin macromolecule impeded the achievement of an adsorption capacity of lignin for polar organic compounds, which would allow it to be cost-competitive with activated carbon, although results with phenol and, to a lesser degree, naphthalene indicate significant potential for achieving competitive capacities. A recommended plan for surface area and structural enhancement is presented on the basis that lignin can be developed as an effective and low-cost adsorbent for polar priority pollutants and/or as an ion-exchange resin for heavy metal wastewater cleanup.

This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

An innovative process for the capture and concentration of hazardous waste compounds, such as heavy metals, organic acids, ketones, etc., which are found in aqueous waste streams has been proposed. The process involves the use of a "pristine lignin" which Georgia Tech investigators had demonstrated as being readily isolated from woody wastes and raw materials by hydrothermal treatment and solvent extraction. The production process (Figure 1) in which the lignin is produced as a by-product during production of sugars from the cellulose fraction of lignocellulose raw materials (and subsequent conversion to fuel-grade ethanol) appeared to be economically feasible. Indeed, the economics would be enhanced by a volume market for the lignin co-product (which, otherwise would be used principally for process fuel). All requisite process equipment for production was commercially available.

Unlike "commercial lignins," the "pristine lignin" is a clean, tractable, relatively low-molecular weight polymer with an expected high degree of organic functionality, unadulterated by adventitious impurities. As such it was consid-

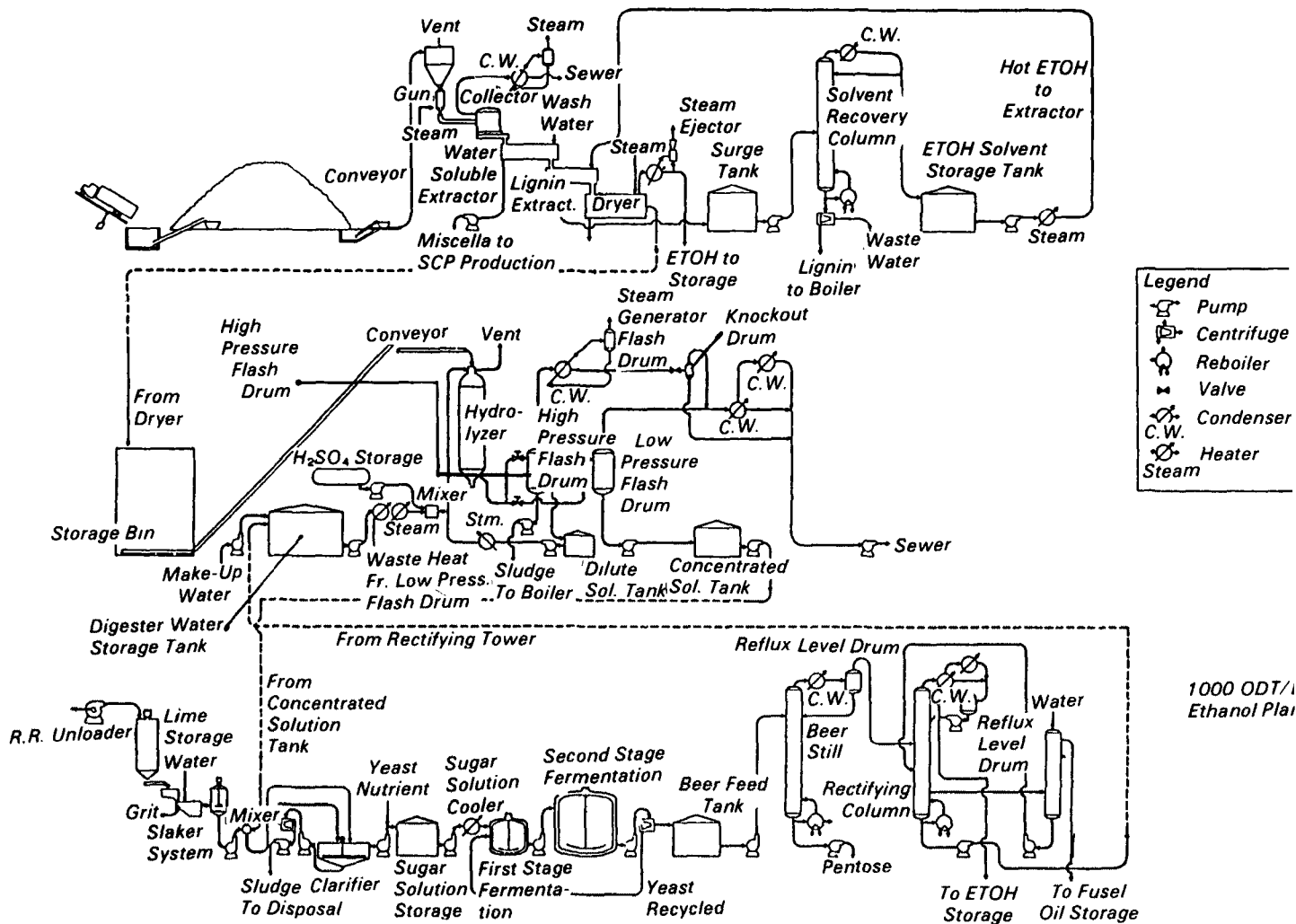


Figure 1. The GIT Process.

ered that the pristine lignin could be employed, in one of three general ways, with or without chemical modification, viz.,

1. Adsorption
2. Ion-exchange chromatography and electron-exchange chromatography
3. Precipitation/Coagulation/Flocculation

The principal economic merit of treating hazardous wastes with lignin was forecast to be its low cost, particularly when compared to adsorbents such as activated carbon and commercial ion-exchange resins (see Table 1).

Table 1. Costs of Lignin and Alternatives

Water Treatment Chemical	Cost
Activated carbon	\$1.19/kg
Ion-exchange resins	2.87/kg
Coagulants	0.20/kg
Lignin (fuel value)	0.03/kg
Lignin (as ligniosulfonate)	0.13/kg

The U.S. Environmental Protection Agency (EPA) estimated that, without regeneration, carbon adsorption costs as high as \$0.42/1000 gallons for a one-MGD plant would be incurred, i.e., an

annual cost of \$153,000. Since the bulk density of Filtrasorb 300 and 400 activated carbon averages 433 kg/cu.m., and pristine lignin ranges from 336 kg/cu.m. (ethanolic) to 606 kg/cu.m. (alkaline), adsorbent vessels should be similarly sized. Therefore, capital costs should be approximately the same assuming different levels of comparative efficiency, it was forecast that lignin could be competitive with activated carbon if it demonstrated only 1/15th the adsorption capacity of the activated carbon. (Note: a median cost of \$0.08/kg for lignin was assumed.) This cost comparison is summarized in Table 2. If one were to proceed in a similar

Table 2. Comparison of Lignin Costs at Various Efficiency Levels Relative to Activated Carbon

Efficiency	Metric Tons Required	Annual Materials Cost
Twice as efficient	64	\$ 5,120
Equal efficiency	128.5	10,280
1/2 efficiency	257	20,560
1/4 efficiency	514	41,120
1/10 efficiency	1285	102,800
1/15 efficiency	1928	154,000
Activated Carbon	128.5	153,000

manner to compare lignin with ion-exchange resins, well-over a 20-fold raw material cost advantage is possible on a simple equivalency basis.

"Pristine lignin" is considered to be exceptionally attractive for several reasons:

1. Low cost
2. Readily disposable after use by incineration, pyrolysis/gasification, and biological (white rot fungus) decomposition.
3. Metals readily reclaimable after treatment with lignin.
4. Biologically resistant.
5. High resistance to degradation/depolymerization.
6. Naturally abundant in nature; coniferous woods (28%), rice hulls (40%), barley straw (16-22%), bagasse (20%).
7. High rich organic functionality, e.g., phenolic hydroxyl groups on the aromatic nuclei. Also, quinonic groups, carboxylic acid groups, carbonyl moieties, etc.
8. Cation complexation, i.e., heavy metal trapping.
9. Organic complexation, e.g., simple phenols, etc.
10. Oxidation-reduction exchange potential due to quinone and diphenoquinone groups possible, i.e., reduced ionic mobility.
11. No need for radical engineering redesign with this technology.

12. Relatively well established science and technology base for lignin modification.
13. Modified versions can range from aqueous solubility (pH-controlled) to organic-soluble.
14. Existing, though small, commercial markets for crude lignin exist. (Most all lignin by-products of pulping processes are burned and most of the heat generated from the lignin is required to evaporate the water from the spent liquor.)
15. Crude alkali lignin and lignosulfonate products have been used as emulsifiers, protective colloids to stabilize emulsions, in ore flotation, electrolytic refining, and industrial wastewater treatment. Sequestering action is used to remove scums and insoluble salts in hard water. Lignosulfonates react with chromates and dichromates to give strongly insoluble materials.

The focus of this research was to concentrate on the use of lignin as an adsorbent and a replacement for activated carbon. It was expected to attenuate heavy metals and organic compounds (especially, polar compounds) in a mechanism not unlike that of humic acids in nature. The research centered on three phases:

1. Isolation of pristine lignin from steam-exploded wood;
2. characterization, chemically and physically, of the lignin; and
3. adsorption studies of lignin and comparison with activated carbon.

A feasibility study to assess the utilization of lignin, isolated from a steam-exploded hardwood (Tulip poplar) with 95% ethanol and 0.1N NaOH, as a potential adsorbent for hazardous waste treatment was conducted. Eight organic compounds and two heavy metals ions were selected from the EPA priority pollutant list for use as model compounds and to allow comparison of lignin isolates with activated carbon.

Adsorption kinetic studies, adsorption size studies, and adsorption isotherms based on the Freundlich equation were completed. The lignin isolates were extensively characterized using IR, UV, C^{13} NMR, and PMR spectroscopy, electrochemical functional group analysis

(Van Krevelen diagrams), differential scanning calorimetry, thermogravimetric analysis, elemental (C, H, N) analysis, gel permeation chromatography, and BET surface area analysis. Carbon adsorption isotherms were produced for compounds not reported in the literature.

The adsorption capacity of lignin for heavy metals (chromium and lead) was found comparable to activated carbon, despite a huge divergence in surface area (0.1 m²/g vs. 1000 m²/g). The surface area discrepancy and the extensive aromatic substitution in lignin macromolecule impeded the achievement of an adsorption capacity of lignin for polar organic compounds. This would allow it to be cost-competitive with activated carbon, although results with phenol and, to a lesser degree, naphthalene indicate significant potential for achieving competitive capacities. A recommended plan for surface area and structural enhancement is presented on the basis that lignin can be developed as an effective and low-cost adsorbent for polar priority pollutants and/or as an ion-exchange resin for heavy metal wastewater cleanup.

Major Findings

Isolation of Pristine Lignin from Steam-Exploded Wood

The steam-exploded wood which was studied extensively in this project was prepared by the hydrothermal decomposition of the hardwood chips of Tulip poplar (*L. tulipifera*) at 350 psig and for a residence time of four minutes. Initial separation processing of this steam-exploded wood centered on extracting the lignin component in "pristine form" by using 95% ethanol and Soxhlet extraction, followed by precipitation into mildly acidified water (pH = 4) and filtration. The average yield of ethanolic lignin isolate was 7.5%. The same feedstock was treated with 0.1N NaOH in a single-stage batch extraction (extraction efficiency found to be >99.4%) and lignin was isolated by precipitation and filtration. The average yield (n = 19) was 31.9% (Range: 26.2 - 39.4%). The recovery represents a 4.25-fold increase in extractable pristine lignin from that of ethanol.

Alkaline extractions were also conducted on steam-exploded aspen hardwood, supplied by Stake Technology (Canada) Ltd., with the caveat that it was not representative of their materials

(although reportedly processed under conditions similar to that of the GIT-processed Tulip poplar) The average yield ($n = 33$) was 25.8%.

Despite variations in workup, both the ethanolic lignin and alkaline lignin isolates produced dry particulates of low surface area. The ethanolic lignin, a light, free-flowing powder contrasted with the dark, friable nature of the alkaline isolate, a state which probably reflects the discrepancy in typical BET surface area values, i.e., $30 \text{ m}^2/\text{g}$ for ethanolic isolate and $0.1 \text{ m}^2/\text{g}$ for alkaline isolate. A significant difference in the molecular weight analyses for all three isolates was found (Table 3).

Table 3. *Molecular Weight and Polydispersity of Lignin Isolates*

	<i>Mw</i>	<i>Mn</i>	<i>Mw/Mn</i>
Ethanolic Lignin (Tulip poplar)	1,379	939	1.47
Alkaline Lignin (Tulip poplar)	2,333	859	2.72
Alkaline Lignin (Aspen)	88,311	2,081	42.4

The alkaline-isolated pristine lignin from Tulip poplar was chosen for detailed adsorption studies because of its high yield (necessary, ultimately, for cost-effectiveness), the promise of adsorptive power (functionality) as suggested by its moderately branched macromolecular structure, and the view that the problem of increasing surface area could be resolved in later studies. (The GPC results suggest that the hydrothermal steam treatment process will require controlled analysis for purposes of preparing a commercial-grade pristine lignin adsorbent.) In the absence of any reported extensive studies of solubility behavior of lignin, a rather comprehensive survey was accomplished in this study to prepare a data base for the establishment of potential alternate extraction procedures. The findings of this study are summarized in Figure 2.

Chemical and Physical Characterization of Pristine Lignin

The extensive characterization program included the following techniques:

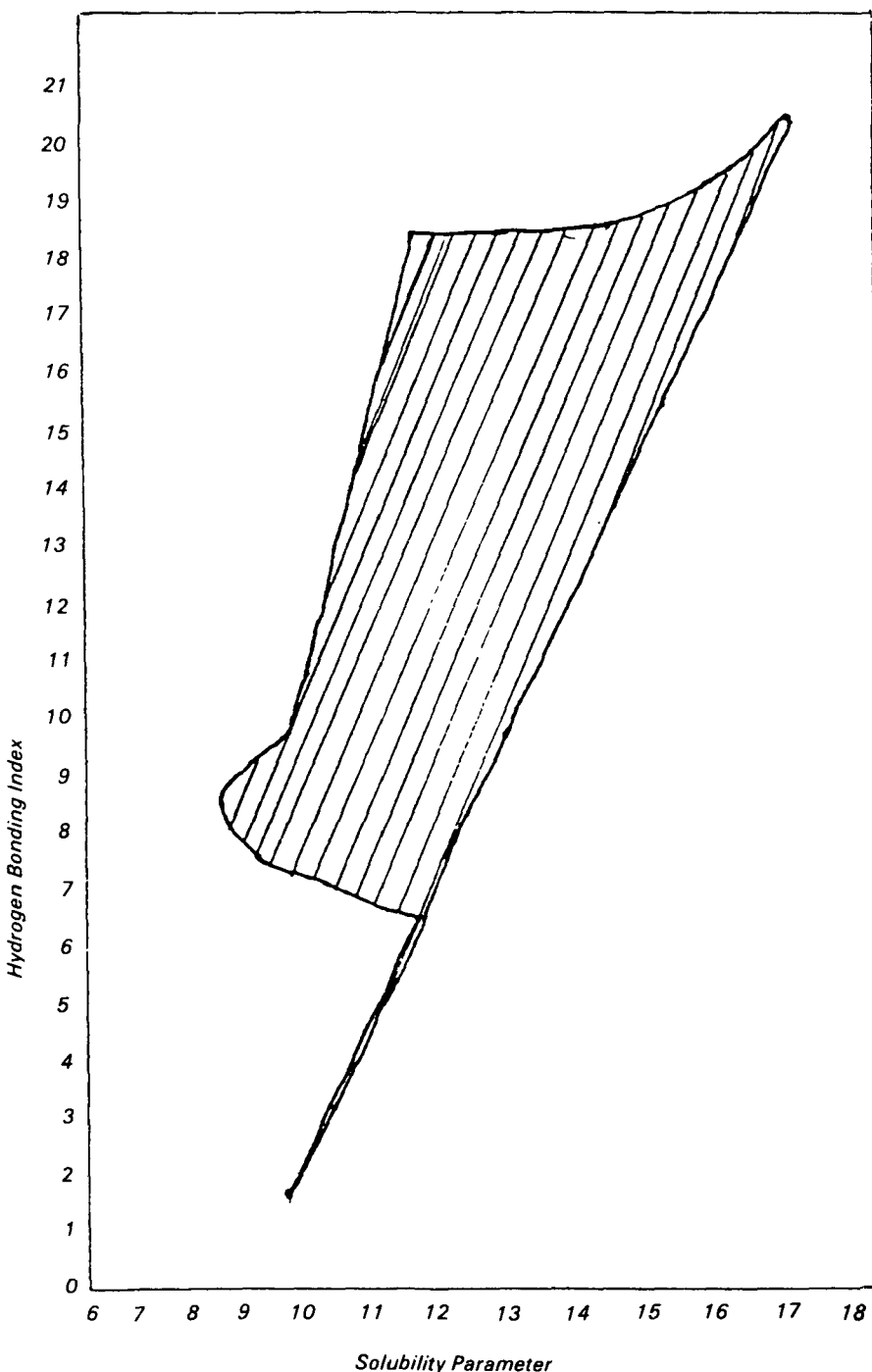


Figure 2. *Lignin solubility behavior.*

1. Moisture, Ash and Klason Lignin
2. Elemental Analysis
3. IR, UV, and NMR Spectroscopy
4. Thermal Analysis (TGA, DSC, Heat of Combustion)
5. Electrochemical Functional Group Analysis
6. Gel Permeation Chromatography
7. Electron Microscopy
8. BET Surface Area Analysis

The results of the characterization indicate that the alkaline lignin isolate from Tulip poplar, on which adsorption studies were focused, were not unrepresentative of the structural features reported in the literature. The major exception was that the molecular weight and molecular weight distribution are relatively low and narrow, respectively. C^{13} NMR spectra in the literature which were performed with softwood lignin showed differences in the aromatic carbon region, as expected. A heavy functional group (phenolic hydroxyl) and aromatic substitution pattern (methoxy and propyl moieties) were found, as expected. Quinonoid and carbonyl groups are present.

Thermal analysis showed lignin to be relatively thermostable in terms of primary bond integrity, that observation being subject to the qualification that crosslinking (and corresponding loss of functionality, i.e., adsorptive capacity) may be masked in thermograms. The higher heating value of lignin isolates (10,350-10,827 BTU/lb, "as is") indicates that lignin would provide a useful combustible matrix for hazardous waste isolation and disposal by incineration

Adsorption Behavior of Pristine Lignin with Selected Model Compounds

Kinetic studies on the model compounds established the equilibrium time required for measurement of adsorption capacity.

Equilibrium concentrations for the model compounds leveled off within two days, undetectable limits being reached after only one day in the cases of bis(2-ethylhexylphthalate) and pentachlorophenol. The time required for achieving equilibrium was less than 12 hours for chromium, while lead required 48 hours. For further adsorption studies, an allowance of four days was made to achieve equilibrium, particularly since large particle sizes (30 x 40 mesh) had been used for the kinetic studies. A preliminary cumulative adsorptive capacity (total of seven organic compounds) of 5 g/kg was estimated for the ethanolic lignin isolate used in this study. It was also noted that an increase in adsorption of model compounds, both organic and inorganic, was achieved with a higher load of lignin, suggesting the possibility of rapid saturation of adsorption sites on the surface of the adsorbent and little penetration (porosity) of the adsorbent

Adsorption Size studies were conducted on three different particle size fractions (30 x 40, 40 x 60, and 60 x 100 mesh) of ethanolic lignin and one of alkaline lignin (60 x 100).

Table 4 shows values for a "cumulative adsorption capacity" of the lignins, at each size range, for the organic compounds in the multicomponent solution (based on the final, equilibrium concentration). The values show that particle size does influence capacity but to a lesser extent than would be predicted by correlation of surface area to reduced particle diameter. This effect strongly suggested that the mechanism of adsorption is confined to surface adsorption sites which are probably saturated relatively quickly and, additionally, allow only partial bonding, i.e., only a fraction of adsorption sites are available, perhaps due to steric hindrance arising from a rapid buildup (deposition) of adsorbed layers.

It was also noted that the ethanolic lignin had a "cumulative adsorption capacity" which was 36% greater than that of the comparable alkaline lignin (60

x 100 mesh). However, the ethanolic lignin isolate had a measured surface area of 30 m²/g for the alkaline isolate, suggesting that the alkaline lignin, if modified to increase its surface area, could potentially exceed the adsorption capacity of the ethanolic isolate. The fact that significantly higher yields of lignin are obtained by alkaline extraction further encouraged the preferential selection of alkaline-isolated pristine lignin for development as adsorbents.

The results of the adsorption size studies with chromium and lead indicated that the alkaline isolate possessed a significantly higher adsorption capacity for heavy metals than does the lignin isolated by the ethanolic extraction procedure. The results are shown in Table 5. If one defines the adsorption ability of a resin by the percentage of metal ions adsorbed based on initial concentration, significant values are obtained for chromium and lead with the alkaline-isolated lignin (60 x 100 mesh), viz., 91% and 80%, respectively.

The difference in behavior towards heavy metals may be due to the ionization

Table 4. Cumulative Adsorption Capacity of Lignin Types and Sizes for a 7-Component Organic Mixture

Lignin Type	Mesh Size	Sieve Opening (mm)	Adsorption Capacity (g/kg)
EtOH-Lignin**	30 x 40	0.59-0.42	3.66
	40 x 60	0.42-0.25	4.43
	60 x 100	0.25-0.15	5.30
NaOH-Lignin*	60 x 100	0.25-0.15	3.90

*Cumulative Adsorption Capacity: based on the sum of the final, equilibrium concentrations for the seven model organic compounds.

**The surface area of the ethanolic isolate (30 x 40 mesh) is 30 sq m/g. A comparable alkaline lignin isolate (30 x 40 mesh) is 0.1 sq m/g.

Table 5. Adsorption Capacity and Ability of Lignin Isolates for Heavy Metal Ions

Lignin	Ion	Adsorption Capacity @ Equilibrium Concentration (g/kg)	Adsorption Ability (% Ion Adsorbed)*
Alkaline (60 x 100 mesh)	Chromium	3.60	91
	Lead	3.56	80
Ethanolic (60 x 100 mesh)	Chromium	2.04	52
	Lead	1.88	42

*Percentage of metal ions adsorbed based on original concentration (C_0); $C_0 = 10$ ppm.

of organic functional groups during the alkaline hydroxide extraction and exchange of sodium ions for protons with the carboxylate, phenolate, etc., anion pairs. Adsorption on alkaline lignin isolates may be expected to be higher with heavy metals ions due to an ion-exchange process which is not a major factor in ethanolic isolates.

Adsorption Isotherms representative of four groups of hazardous waste compounds on alkali-isolated pristine lignin were determined. The compounds were representative of acid- and neutral-extractables (phenol, naphthalene), pesticides (2,4-dichlorophenoxy acetic acid), purgeables (trichloroethylene), and heavy metals (chromium). The experimental data for phenol, naphthalene, and chromium on pristine lignin were compared to the experimental data reported by EPA or determined in this study for the compounds on activated carbon. The comparisons were based on Freundlich parameters selected from the adsorption isotherms of the given model compound at one arbitrary, but common, equilibrium value.

Under comparable conditions, the relative adsorptive capacity of activated carbon for phenol was 46 g/kg. For pristine lignin, the relative adsorptive capacity was 1.6 g/kg. To achieve the same equilibrium concentration, a loading of adsorbent of 100 mg/l of activated carbon vs. 3000 mg/l of pristine lignin would be required. Therefore, the "efficiency" of pristine lignin is 1/30th that of activated carbon or 50% below the minimal 1/15 target value originally established as a criterion of cost-effectiveness. However, the activated carbon adsorbents have surface areas of 1000 m²/g whereas the alkaline-isolated pristine lignin had a value of only 0.1 m²/g.

A similar comparative analysis was made for naphthalene. The relative adsorption capacities were 184 g/kg and 1.6 g/kg, for activated carbon and pristine, respectively. The corresponding adsorbent loads were 25 mg/l and 3000 mg/l.

For the case of heavy metals, pristine lignin appears to have significantly more potential as an adsorbent vis-a-vis activated carbon. For essentially similar experimental conditions, the relative adsorption capacity for chromium on pristine lignin is 8.7 g/kg vs. 27.8 g/kg with activated carbon. The adsorbent doses required to achieve a similar residual concentration were 1.0 g/l and

0.25 g/l for lignin and carbon, respectively.

The preferred affinity of pristine lignin for phenol and chromium (and, to a lesser extent, naphthalene) among the model hazardous waste compounds is indicative of a highly polar adsorption process at the surface of the lignin. Heavy metal adsorption is probably due in large part to a cation exchange mechanism. Little, if any, contribution is made to adsorption processes by a porous microstructure which is characteristic of commercial adsorbents. Indeed, the introduction of porosity, and concomitant increase of surface area, is required for pristine lignin to be used as an adsorbent.

Conclusions

1. If the surface area of pristine lignin isolates could be substantially increased, they are potentially competitive with activated carbon on a cost-effectiveness basis for adsorption of polar compounds among priority pollutants.
2. The adsorption capacity of alkaline-isolated lignin for heavy metals (chromium and lead) is approximately equivalent to that of activated carbon (9 g/kg vs. 28 g/kg) despite a huge divergence in surface area (0.1 m²/g vs. 1000 m²/g). The applicability of pristine lignin for polishing of heavy metal wastewater is suggested with little further modification being required.
3. The adsorption capacities (for model organic compounds) of specific lignin isolates, which were examined in this study, were less than those of activated carbon and they failed to achieve the 1/15th-to-1/20th value of carbon adsorption capacity (although phenol results approached the criterion) which has been targeted as a technical and economic break-even criterion for comparability of lignin and activated carbon. The adsorption capacities for phenol under comparable conditions with activated carbon and pristine lignin, were 46 g/kg and 1.6 g/kg, respectively. Corresponding adsorbent loads were 100 mg/l and 3000 mg/l, respectively. Naphthalene was adsorbed by lignin, but the disparity was greater. Only marginal adsorption of trichloroethylene was evident and there

was a general insensitivity increased adsorbent load for the purgeable compound.

4. The major impediment to achieving comparability on technoeconomic grounds by lignin with activated carbon is attributed to the intrinsically low values of surface area (order of 0.1 m²/g for alkaline isolated lignin). In general, adsorbents used in commercial adsorption processes exhibit high surface area per unit of weight (100-1000 m²/g).
5. Another significant impediment to the realization of higher adsorption potential of lignin appeared to be the state of extensive substitution of the aromatic nuclei in the macromolecular structure and a high methoxyl group content (vis-a-vis phenoxy hydroxyl content). Since experiments were conducted with a single source of steam-explosion wood processed under a fixed set of conditions (350 psig, 4 minute), the nature of the lignin in the starting material was itself fixed, i.e., there was no flexibility in varying or modifying the composition of the lignin isolates which were studied, other than in the fraction of the lignin component which was extractable (8% for ethanolic lignin and 32% for alkaline lignin). If conditions could be optimized during steam-explosion (autohydrolysis), methoxyl group content could be "uncapped," increasing phenolic hydroxyl content and/or establishing a higher quinone character, with the possibility of greater electron delocalization, hydrogen bonding, and other secondary bonding forces becoming operative during adsorption of polar compounds.
6. The surface activity of lignin isolates, though seriously limited by the available active sites on a very limited surface area, did show preferred affinity for phenol and chromium (and to a lesser degree for naphthalene) which is indicative of a highly polar adsorption mechanism at the surface. The magnitude of such effects should be enhanced by the induction of micro- and macro-porosity in the lignin isolates.

7. The adsorption kinetics study revealed relatively rapid equilibrium of heavy metals by alkaline lignin suggesting primary bonding forces at work, probably via a cation exchange mechanism involving residual sodium ions and the carboxylate or phenolate anions of the lignin macromolecule. In these studies, alkaline lignin (60 x 100 mesh) removed 91% of the original chromium concentration and 80% of the lead ion concentration. Despite a higher surface area, ethanolic lignin isolates did not perform as well: 52% and 42% for chromium and lead removal, respectively.
8. The adsorption isotherm curves, developed for the Freundlich isotherm equation, were of the S-1 type (Giles classification). The behavior is explained by the force of interaction between adsorbed molecules being significant relative to that between solute and adsorbent. Solute molecules tend to be packed in rows or clusters on the surface and the condition is encouraged with water as solvent, which itself is strongly adsorbed on a polar adsorbent (lignin) and when the solute is mono-functional (as with phenol).
9. The experimental evidence *in toto* suggests that it would be premature to conclude that pristine lignin cannot be developed further to be a low-cost, efficient adsorbent for polar organic priority pollutants or a cost-competitive and effective ion-exchange resin for heavy metal hazardous waste treatment. As an adsorbent, its thermal characteristics (higher heating value of over 11,000 BTU/lb strongly suggest its disposability thermally. Alternatively, biochemical (fungal) degradation may be used. In both disposal cases, the hazardous wastes would be concentrated.

Recommendations

Despite the limitations of time and resources that are associated with feasibility studies such as this one, there appears to be ample evidence that lignin, which is isolatable from steam-exploded wood, when the latter material is itself processed to optimize the extractability quantitatively and qualitatively of the modified lignin, possesses the potential

of being either a low-cost, high-efficiency adsorbent for polar compounds which is competitive with activated carbon or a precursor for a highly efficient ion-exchange resin for cleanup of heavy metal ions.

A Phase II study is recommended with the objective of producing a steam-exploded or autohydrolyzed hardwood under operational conditions, whereby lignin can be chemically debonded from the carbohydrate (cellulose and hemicellulose) components of wood so that it is readily extracted in high yields and in a chemical form in which deleterious condensation (lignin-lignin or lignin-carbohydrate secondary reactions) is minimized and in which phenolic hydroxyl and quinonic content is maximized. In addition, the lignin should be isolated, preferentially, by chemical process operations that provide a surface area of 100-1000 m²/g. The surface area enhancement may be achieved by one or more of the following techniques:

- (a) mild crosslinking associated with "blowing agents"
- (b) controlled sol-gel techniques
- (c) spray drying
- (d) uniform coating of low-cost inert supports (with or without subsequent removal of supports)
- (e) optimized solvent-nonsolvent precipitation systems

In a parallel study, the pristine lignin isolate would be directly compared to commercial weak-acid and cation exchange resins. Also, with modification, because of the highly aromaticized structure, derivatives of pristine lignin representative of the major classes of ion-exchange resins will be prepared, since the low cost of the lignin isolate (e.g., 5-6¢/lb for phenol) allows derivatives to be highly cost-competitive with the expensive commercial synthetic ion-exchange resins (e.g., \$3/kg).

In summary, the following study elements are proposed:

1. Investigate/identify preferred conditions for steam explosion or autohydrolysis to produce preferred chemical structure in the lignin isolate.
2. Qualitatively characterize lignin isolates to enhance the basic chemical structure (a) for preferen-

tial adsorption of polar hazardous waste compounds, and (b) for facile modification of the structure to produce ion-exchange resins

3. Maximize yields of extractable lignin from steam-processed hardwoods.
4. Develop a (preferably one-stage) process for producing high surface-area (100-1000 m²/g) lignin isolates with minimal mitigation of surface activity.
5. Perform kinetics and adsorption isotherm studies with selected model polar compounds drawn from the EPA list of priority pollutants using both modified lignin isolates and activated carbon.
6. Prepare chemically modified lignin derivatives for use and evaluation as ion-exchange resins for the cleanup of heavy metal pollutants (and ions, possibly). Minor modifications include possibilities of (a) oxidation to increase acidic, phenolic, quinonic, ketonic, or aldehydic content, and (b) increasing crosslink density/gelation through thermal- or thermochemical treatments. Major modification involves chemical substitution, for example, of the aromatic nuclei or preparation of strong-base, anion-exchange resins by chloromethylation followed by reaction with a trialkyl amine.
7. Characterize the modified lignin ion-exchange resins as to their porosity, surface area, ion capacity, volume stability, swelling, etc.
8. Prepare a final report on the benefits, technical and economic, of employing lignin as an adsorbent or as an ion-exchange resin for hazardous waste treatment.

Daniel J. O'Neil, Christopher J. Newman, E. S. K. Chian, and H. Gao are with Georgia Institute of Technology, Atlanta, GA 30332.

T. David Ferguson is the EPA Project Officer (see below).

The complete report entitled "An Evaluation of Pristine Lignin for Hazardous Waste Treatment," (Order No. PB 87-191 664/AS; Cost: \$24.95, subject to change) will be available only from:

National Technical Information Service

5285 Port Royal Road

Springfield, VA 22161

Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Hazardous Waste Engineering Research Laboratory

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Cincinnati, OH 45268

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