LYSINOL: A RENEWABLY RESOURCED ALTERNATIVE TO PETROCHEMICAL ETHYLENEAMINES AND AMINOALCOHOLS

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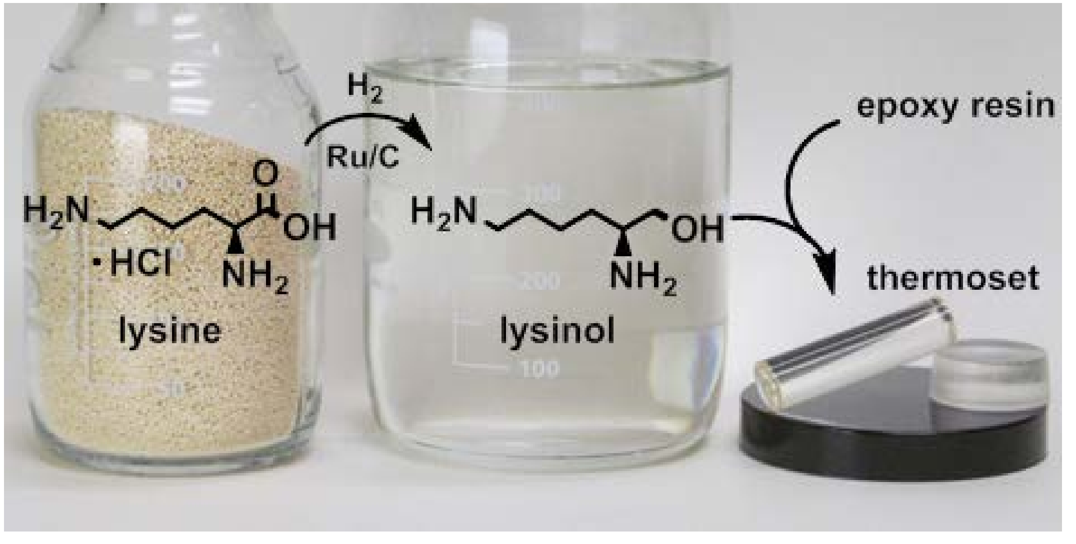
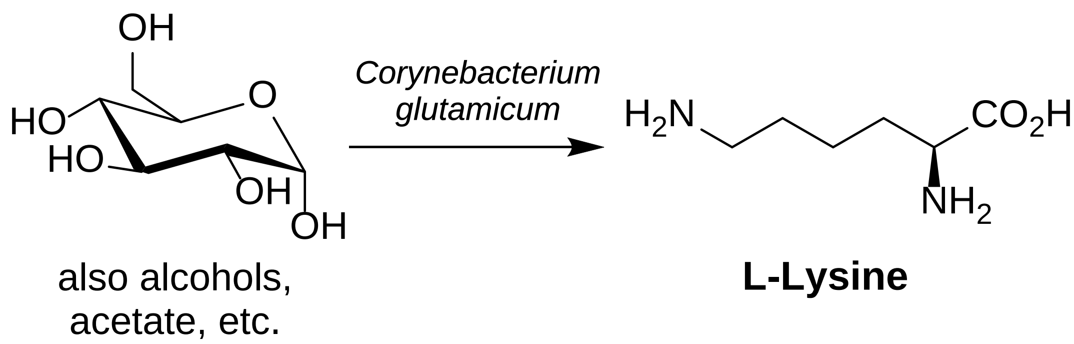
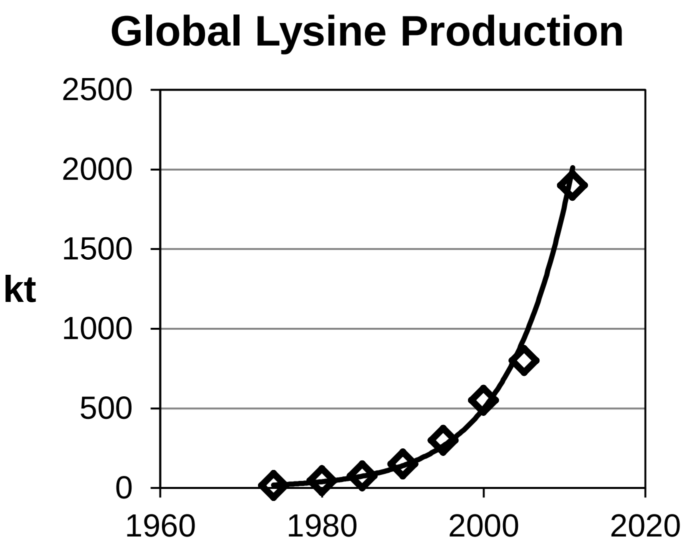


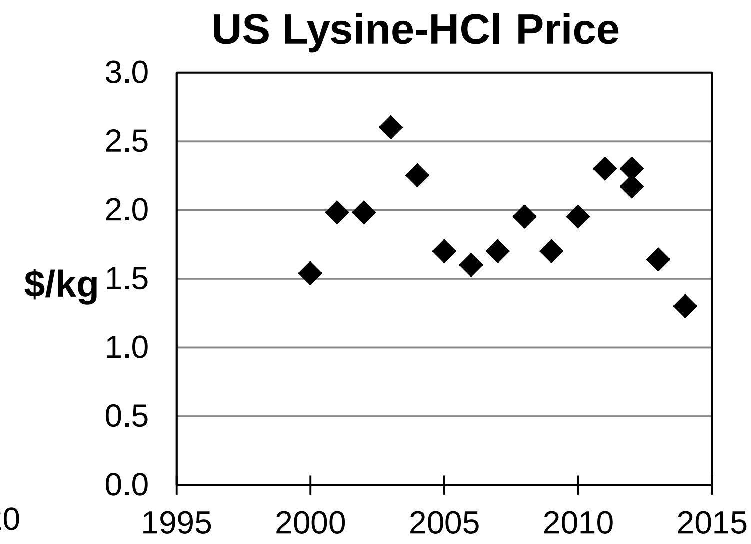
Lysine



- Second largest production volume of any amino acid (glutamic acid/MSG #1).
- Essential amino acid, used almost exclusively as animal feed (swine, poultry).
- 50 Year old fermentation process from glucose:
  - Net 4 e^- reduction, selectively break five C-OH bonds, selectively make two C-NH_2 bonds.
- High yield: ~ 0.5 g lysine-HCl/g glucose *vs*. 0.56 g/g theoretical yield (90%).
- Commodity volumes: *ca*. $2x10^9$ kg per year and continues to grow.
- Cheap
- "Lysine" = lysine monohydrochloride, 80 % lysine content
  - Lysine sulfate and lysine free base (50 % aq solution) are also available albeit in smaller production volume.

Lysine Economics





Estimate:
$2/kg market price,
$1.5/kg cost of
manufacture.

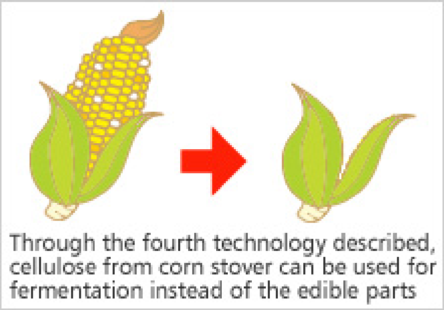
China:
ca. $2/kg average (2012)
$0.85/kg April 2014

Ongoing capacity increases in the Asia, US, Brazil, and Russia despite price pressure.

Capacity increases accompanied by significant R&D to further reduce cost.

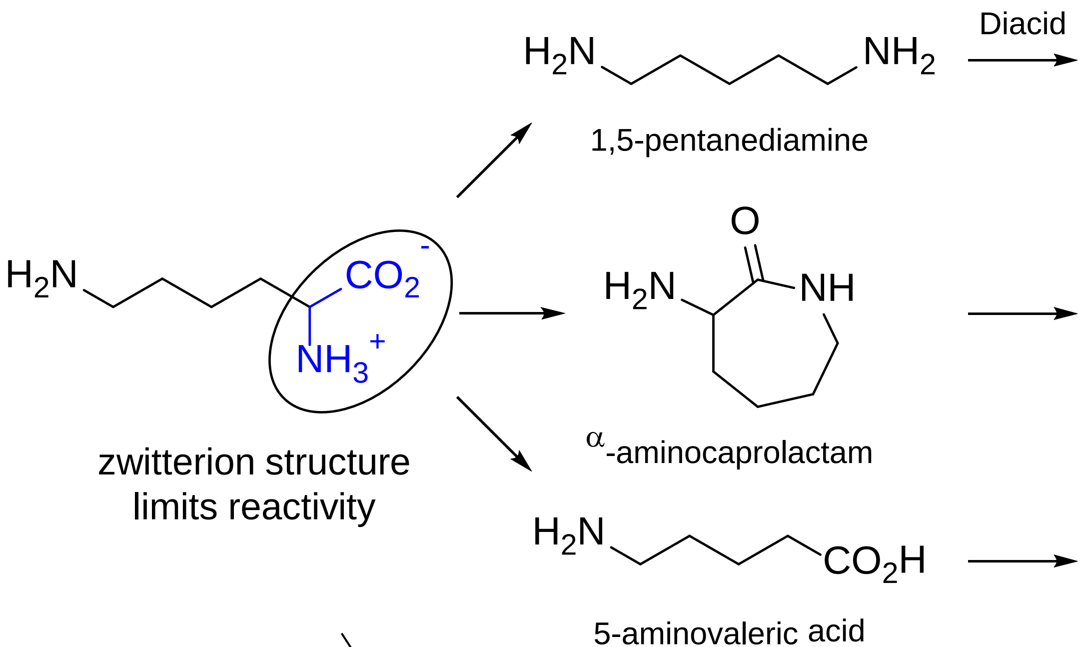
Ajinomoto multigenerational lysine R&D
Lysine from non-food sources

http://www.ajinomoto.com/csr/earth/climate.html



"cellulosic lysine"

Lysine as a chemical intermediate: Polyamides



Nylon 5,# copolymers

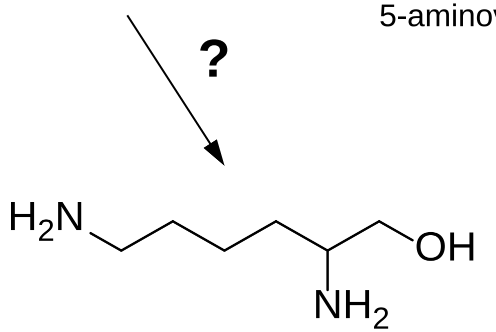
Ajinomoto/Toray, Cathay, others

Nylon 6 (via caprolactam)

Frost (Amyris), WO2005/123669A1
Wicks (Draths), WO2010/011967A1

Nylon 5

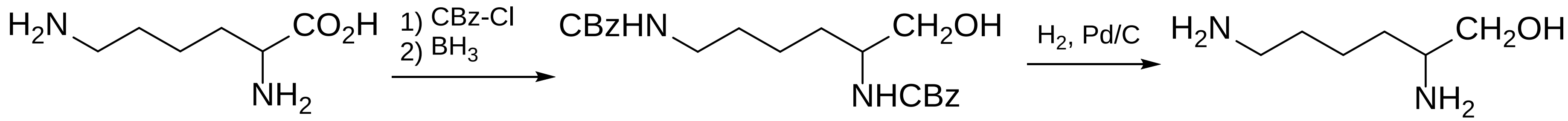
Pukin, *et al.*, *J. Mol. Catal. B: Enzym.*, 2010



Lysinol
(2,6-diamino-1-hexanol)

Lysinol: Literature

- Only 23 unique citations refer to lysinol (*S, R*, or *rac*), derivatives, or salts.
- A single reference describes the synthesis, isolation, and characterization of lysinol free base.
- Literature examples are limited to multi-step, stoichiometric conversion of lysine.



Kihara, *et al*., *J. Polym. Sci., Part A: Polym. Chem*., **1996**, *34*, 2173.

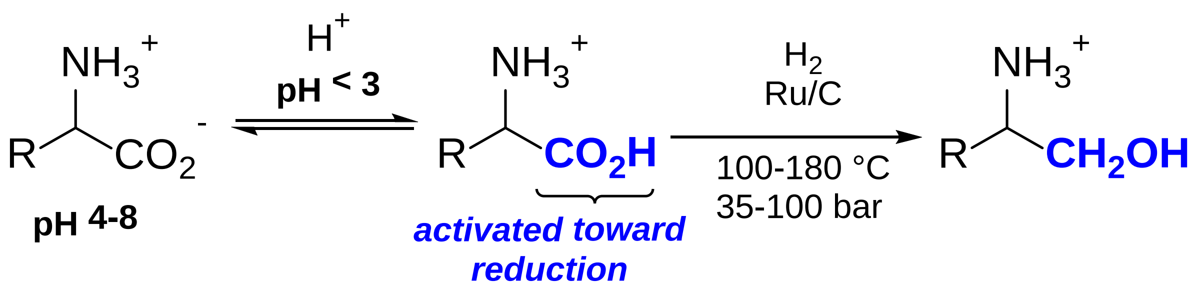
Amino Acids to Amino Alcohols

Carboxylic acids and esters are not easily hydrogenated:

$$RCO_2R' + H_2 \xrightarrow[\text{200-280 °C; 200-300 bar}]{\text{Ru/C}} RCH_2OH + R'OH$$

Catalyst Selection Guide, Johnson Matthey, 2007;
Manyar, *et al., Chem. Commun*., **2010**, *46*, 6279

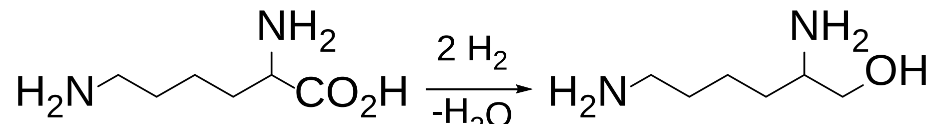
Amino acids are easier - *at acidic pH*:



Examples for alanine, serine, valine, leucine, proline,… <u>but not lysine</u>.

K. P. Pimparkar; D. J. Miller; J. E. Jackson, *Ind. Eng. Chem. Res*. **2008**, *47*, 7648
F. T. Jere; J. E. Jackson; D. J. Miller, D. *Ind. Eng. Chem. Res*. **2004,** *43,* 3297
Urtel, et al., WO2005077871 (BASF)
Antons, et al., WO9938838 (Bayer)

Lysine Hydrogenation



lysine → lysinol

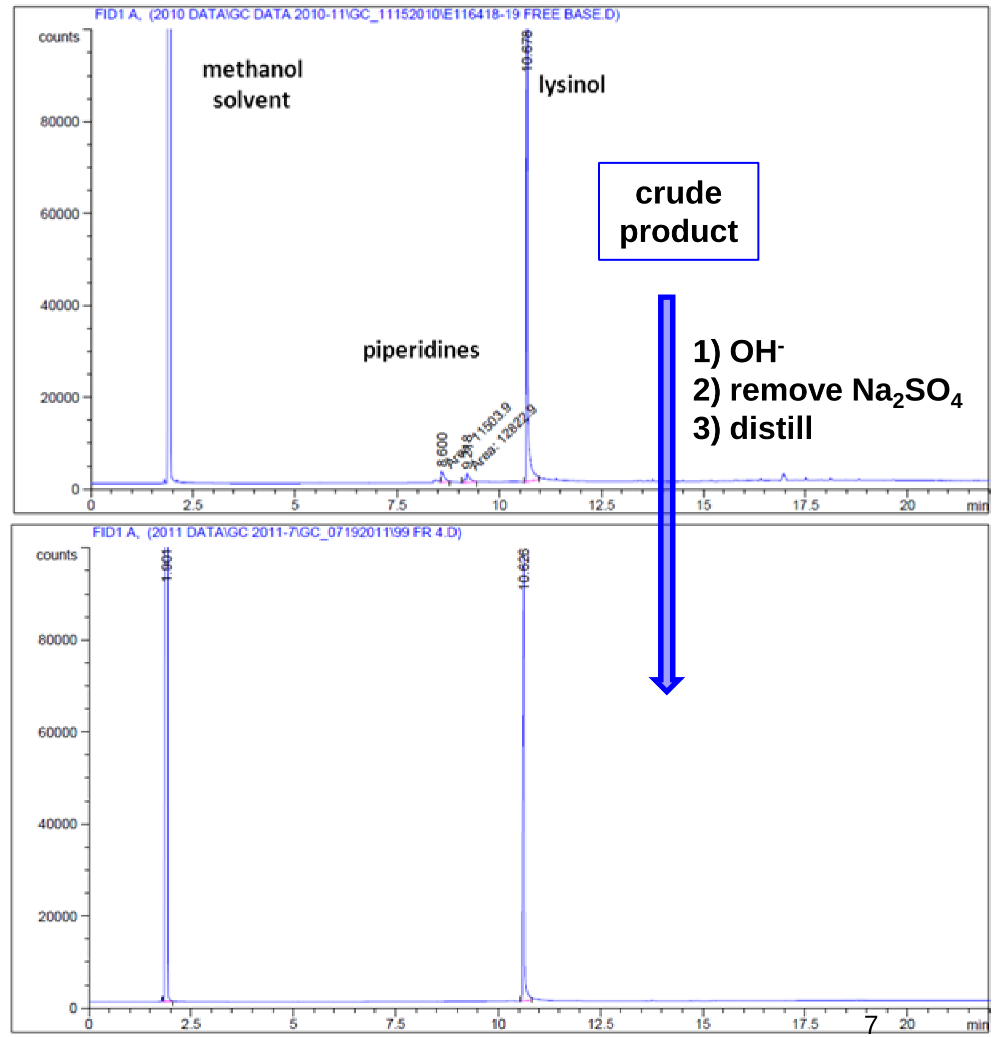
Conditions:

- 5 % Ru/C
- 100-120 °C
- 50-70 bar
- 20-30 wt% lysine in water
- Initial pH ~ 1.8-2 (~1.1 eq H_2SO_4)

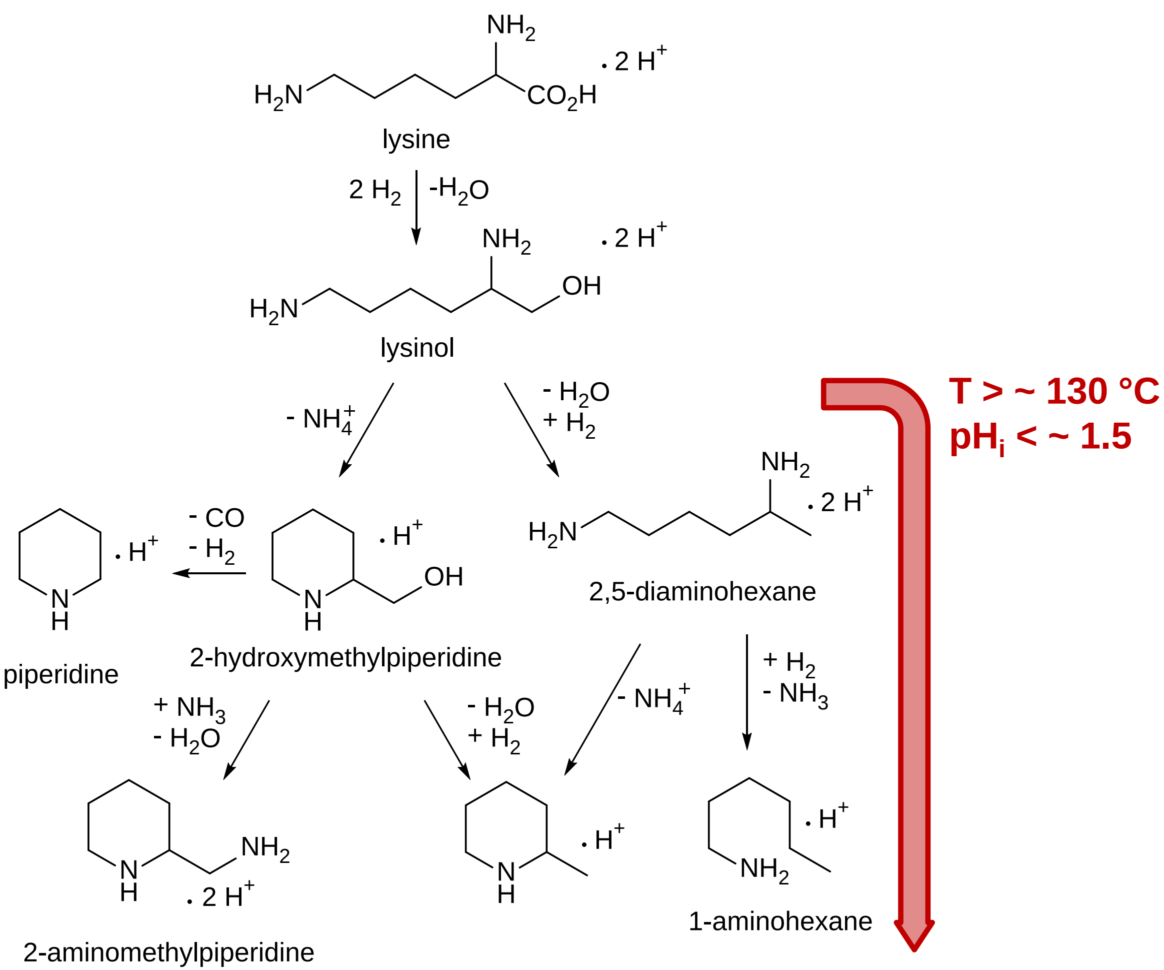
Results:

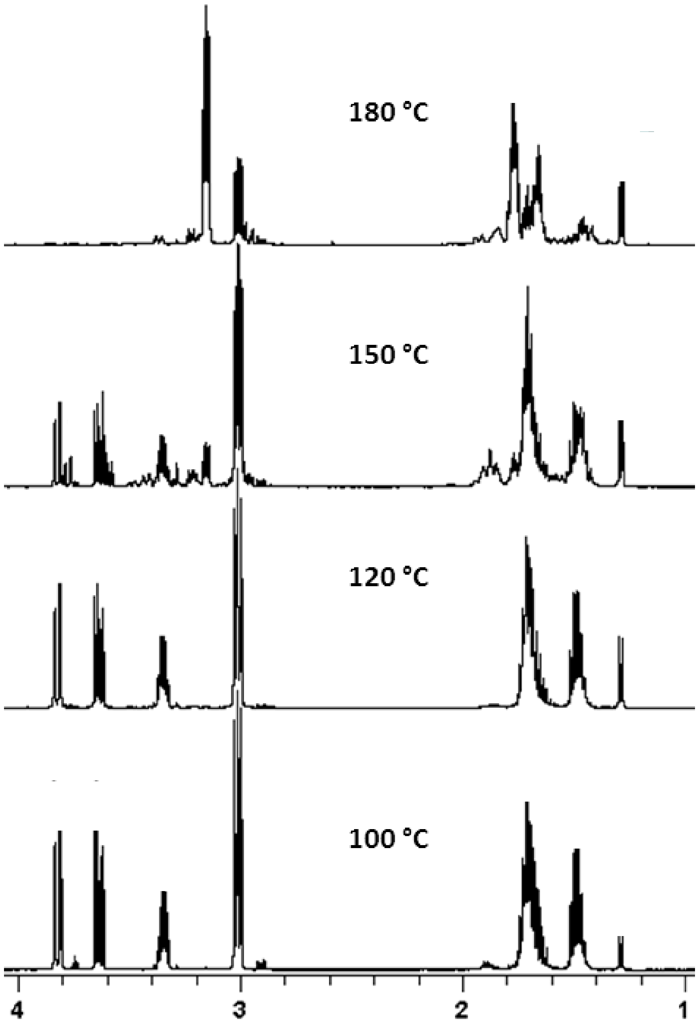
- Quantitative lysine conversion
- 90+ % lysinol selectivity
- 50-70 % isolated yields of high purity lysinol

***Feed Grade* lysine also works:**
Lys-HCl
Lys-sulfate
50% aq base



Product Distribution

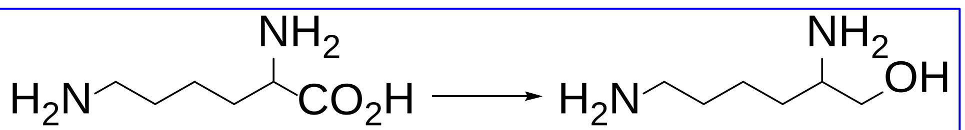




Hydrogenation Kinetics

1^{st} order in H_2
1^{st} order in catalyst
0 order in lysine

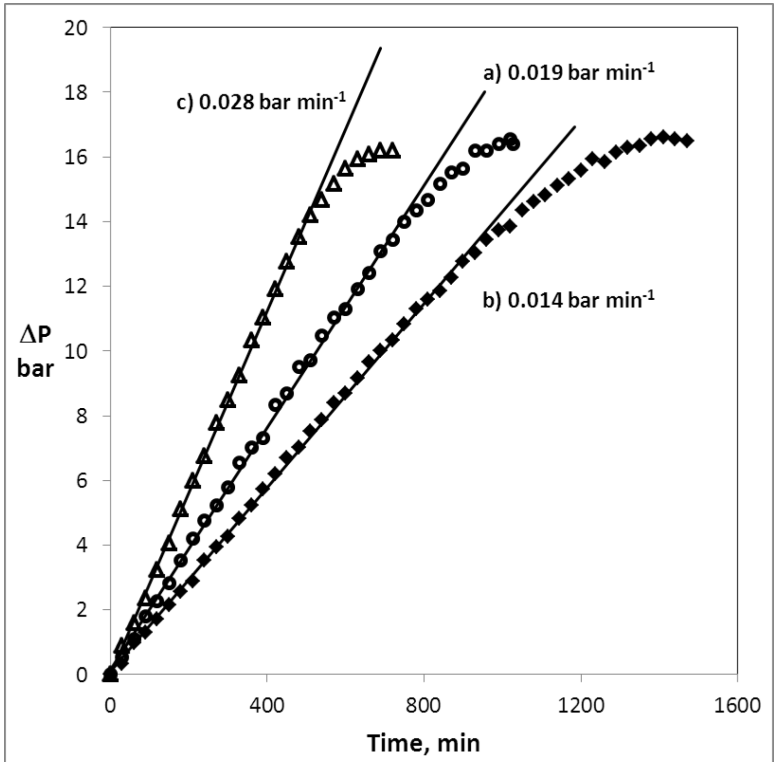
Alanine hydrogenation kinetics: Jere, F. T.; Jackson, J. E.; Miller, D. J. *Ind. Eng. Chem. Res.*, **2004**, *43*, 3297

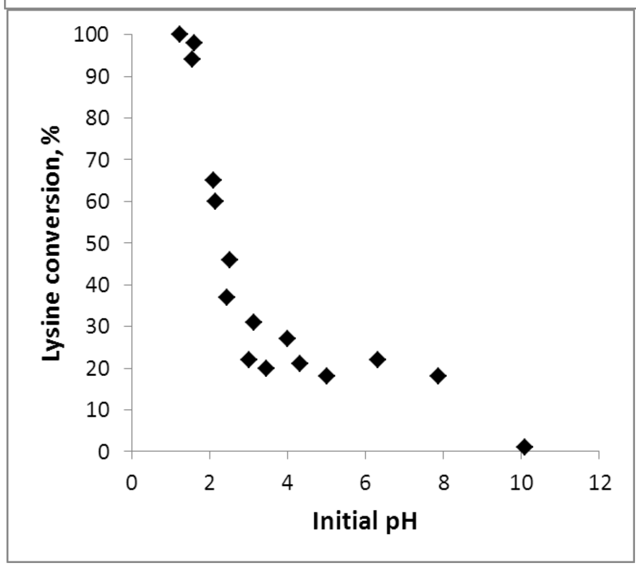


pKa_1= 2.2 pKa_2 = 8.8 pKa_3= 10.5 pKa_1= 10.5 pKa_2 = 12.8

Lysinol is a stronger base than lysine
⇨ pH increases with increasing conversion

Initial pH	Final pH	Conv
1.3	3.5	>99%
2.2	6.9	75 %

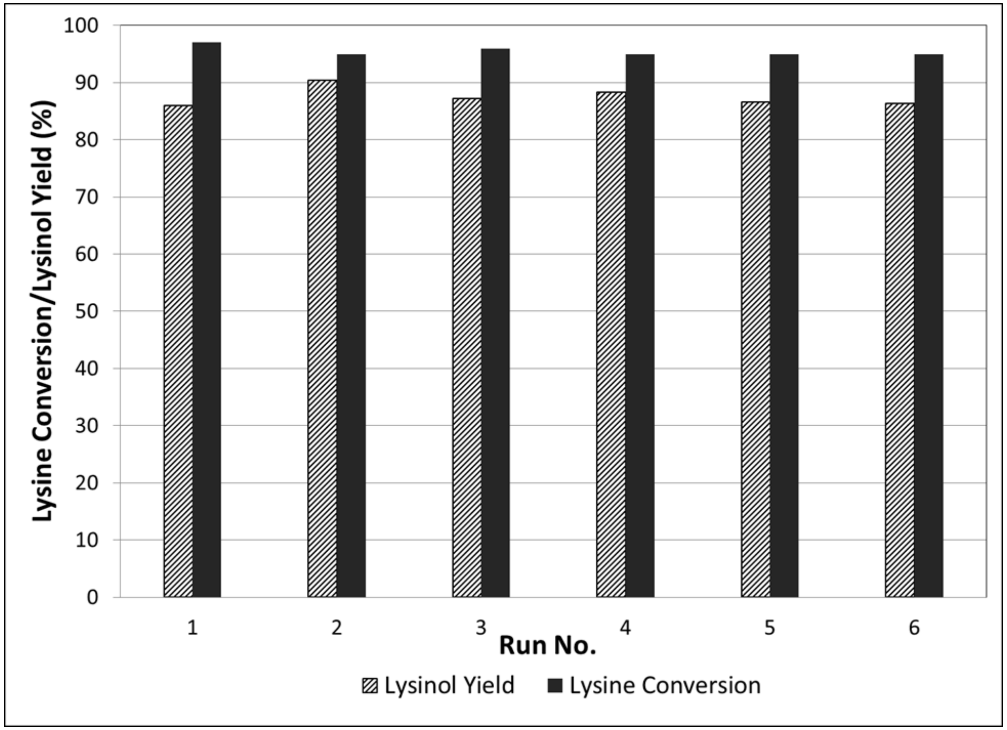




Catalyst Recycle

Hydrogenation rates are relatively low, large catalyst charges are used to reduce batch time.

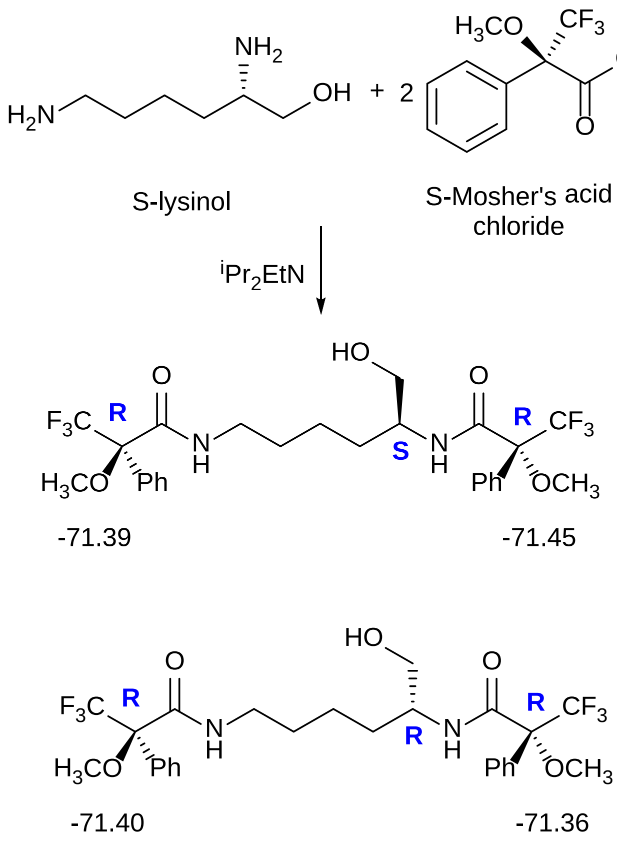
Catalyst is routinely recovered and reused.

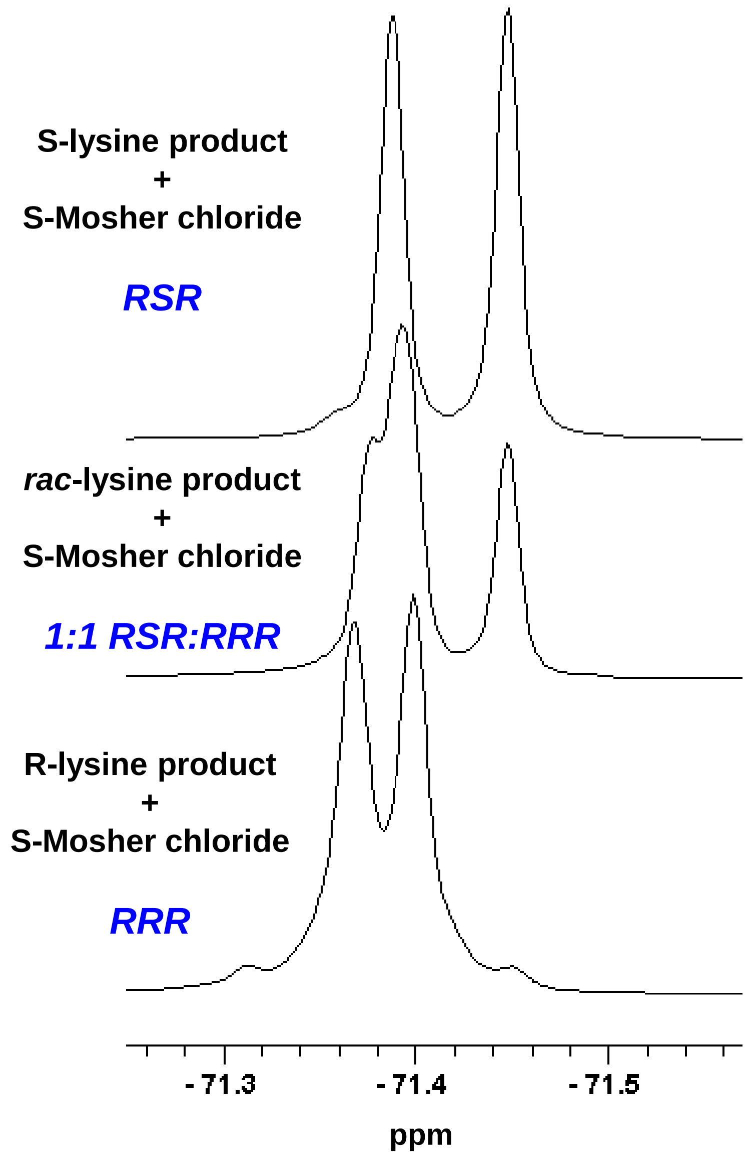


Filtrate [Ru] is below detection limits (< 1 ppm)

3 g lysine (10 % aq), 1.1 equiv H_2SO_4, pH_i = 1.7; 1 g 5% Ru/C, 120 °C, 65 bar H_2, 16 h.

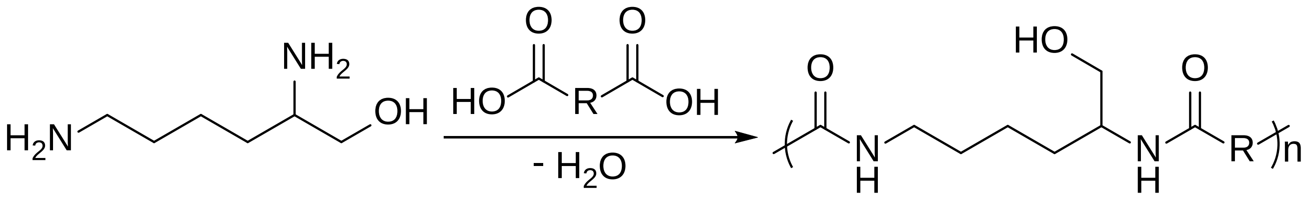
Stereoretention: Mosher amide & ^{19}F NMR





Result via peak deconvolution:
88-96 % ee, stereochemistry largely retained

Lysinol Polyamides



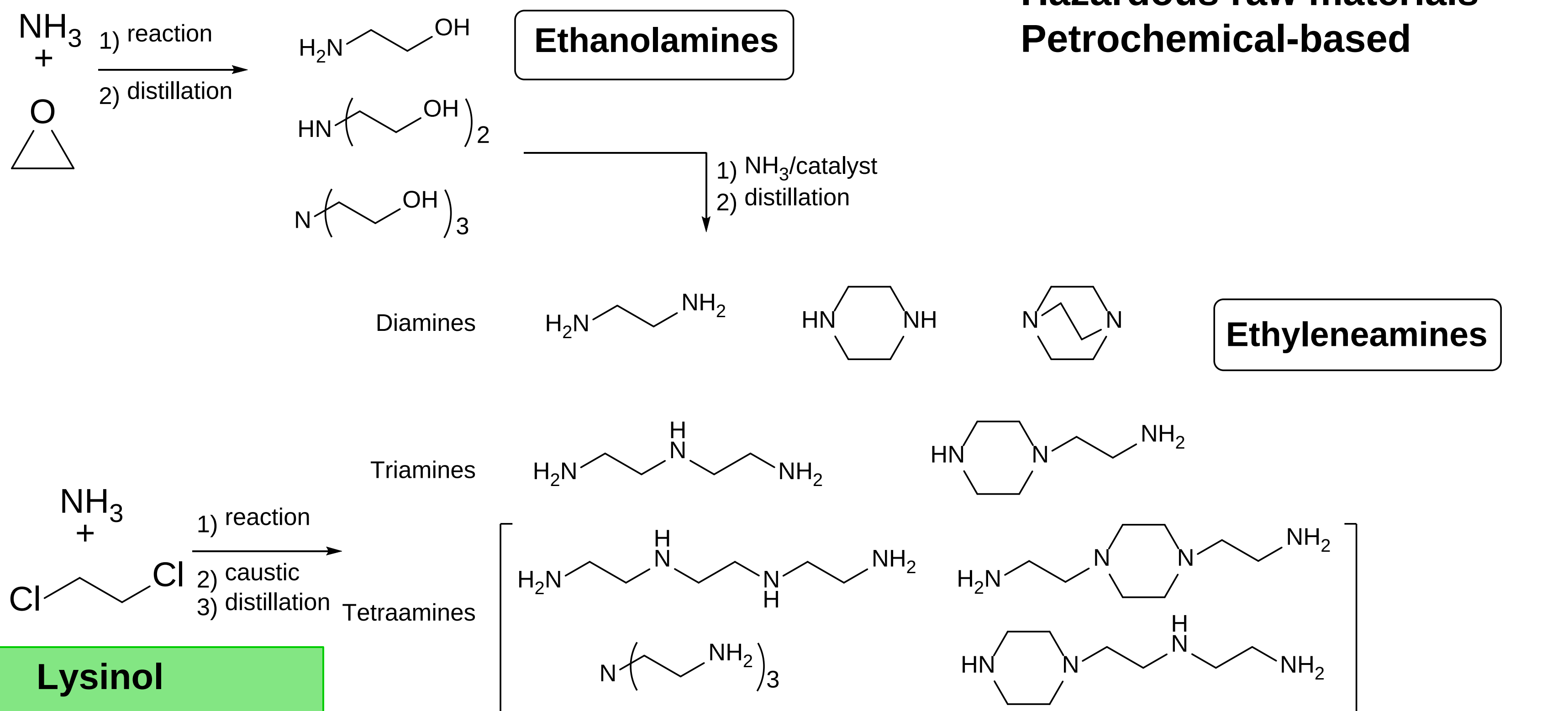
Lysinol:adipic acid (R= $(CH_2)_4$) copolymer is insoluble, cannot be melt processed.

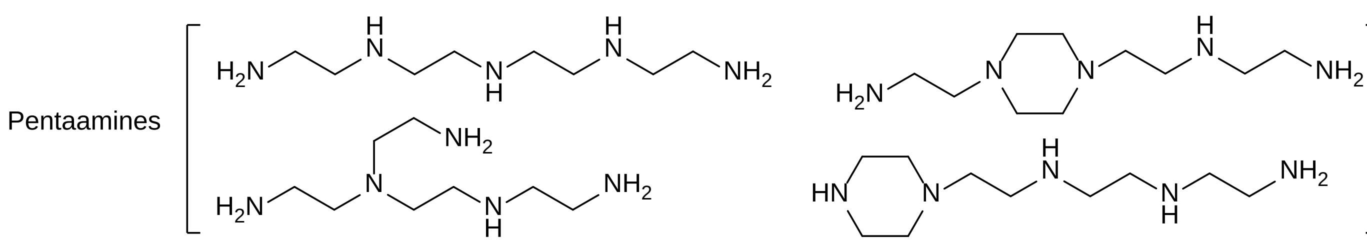
Example	Mole % lysinol	Mole % HMD	Mn	Mw	Mz	PDI	1st mp, °C	2nd mp, °C
Nylon 66	0	100				**2**	264	
5%	5	95	22800	70330	502000	**3.1**	253	250
10%	10	90	6704	1630	28450	**2.4**	244	236
15%	15	85	**insol**				231	222
20%	20	80	**insol**				215	206

Conclusion: Cross-linking occurs *via* ester formation, therefore lysinol based thermoplastic polyamides are not accessible.

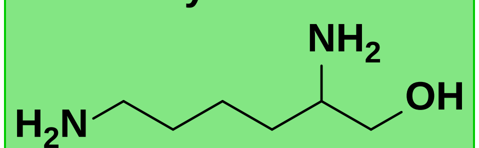
Polyfunctional Amines

Complex product mixtures
Hazardous raw materials
Petrochemical-based





Lysinol



Similar functionality, structure, and molecular weight

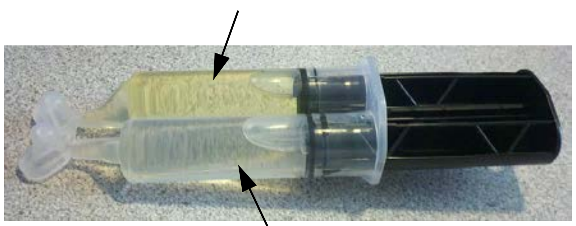
Ethanolamines, Ethyleneamines

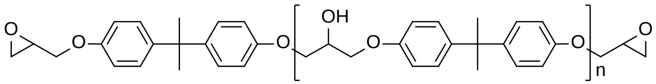
Pricing: Ethanolamines ~ $1.9/kg; Ethyleneamines ~ $ 4.5-5.5/kg

Ethyleneamine Markets
Global production: 2x10^{9} kg/yr

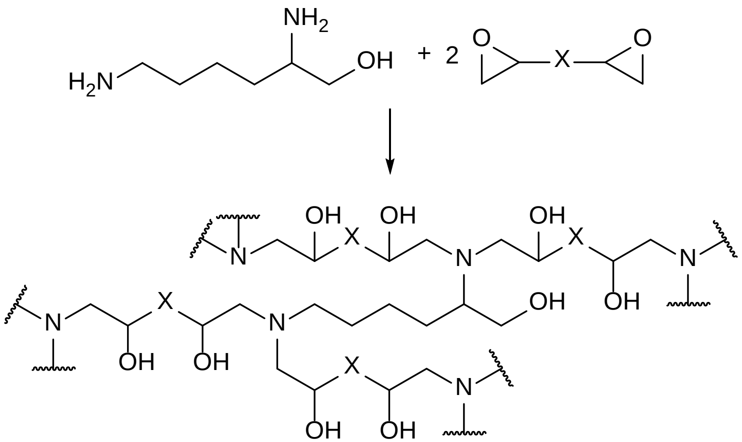
- Chemical Intermediates
- Polyamide/Epoxy
- Chelants
- Fungicides
- Lube Oils
- Bleach Activator
- Paper Resins
- Piperazine Derivatives
- Oil Field Chemicals
- Urethanes
- Surfactants
- Fabric Softeners
- Asphalt
- Fuel Additives

amine 'hardener'





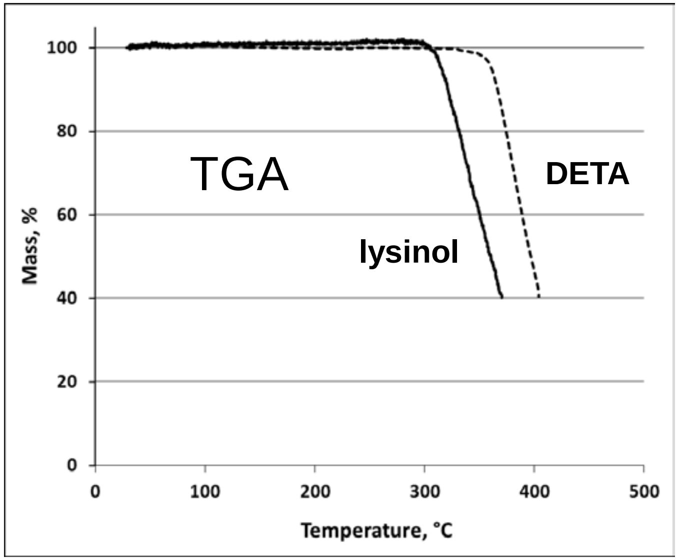
BADGE



Epoxy Thermosets: Lysinol vs. Ethyleneamine (DETA)

Formulated at 1 NH per epoxy
Tack-free after several hours @ RT
Cured @ 60-100 °C

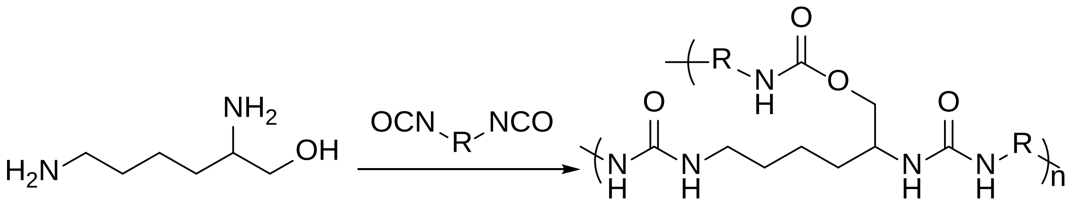
Thermoset properties are nearly indistinguishable



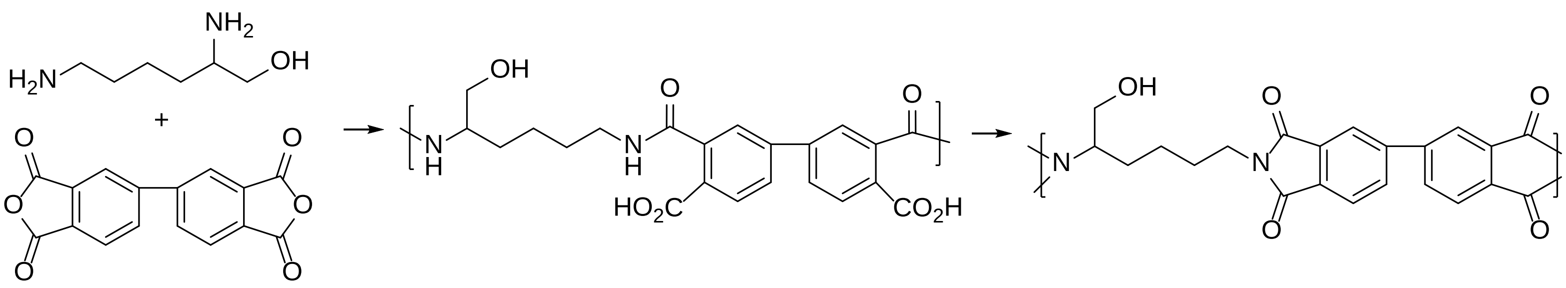
	Lysinol	Diethylenetriamine
Lap Shear		
Tensile Strength, MPa	4.6(1.1)	4.7(0.5)
Compression		
Compression Modulus, MPa	1678(133)	1489(69)
Strain at Yield, %	11.6(0.5)	16.3(0.4)
Stress at Yield, MPa	103(1)	104(1)
Nanoindentation		
Instrumented Hardness, MPa	228(48)	199(35)
Reduced Modulus, MPa	3506(412)	3287(279)
Chemical Resistance, % mass gain		
50% aq NaOH	5.5(2.5)	5.0(1.1)
30% aq H_2SO_4	3.8(1.0)	4.4(0.5)
H_2O	2.4(0.2)	2.3(0.4)
3.5% aq NaCl	2.6(0.3)	1.9(1.5)
acetone	6.9(2.3)	5.4(1.9)
toluene	0.4(0.1)	0.2(0.4)

Other polymers from lysinol

Polyurea/polyurethane thermoset



Polyimide (solution processible)



Take home message

Lysine and lysinol are worth our attention!

Renewable, inexpensive, abundant and non-toxic raw materials

Water solvent and co-product

High selectivity catalysis

Acknowledgments

Mark Scialdone

Pranit Metkar

Ellen Baldassare
Charlie Bellini
Jan Hytrek
Bryan Cheng
Dupont CR&D

Joe Bozell for
1) reading my paper and
2) inviting me to share my work at this conference