Synthesis of biobased *N*-methylpyrrolidone by one-pot cyclization and methylation of γ-aminobutyric acid

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N-Methylpyrrolidone (NMP) is an industrial solvent that is currently based on fossil resources. In order to prepare it in a biobased way, the possibility to synthesize NMP from γ-aminobutyric acid (GABA) was investigated, since GABA can be obtained from glutamic acid, an amino acid that is present in many plant proteins. Cyclization of GABA to 2-pyrrolidone and subsequent methylation of 2-pyrrolidone to NMP was achieved in a one-pot procedure, using methanol as the methylating agent and a halogen salt (*i.e.* ammonium bromide) as a catalyst. A selectivity above 90% was achieved, as well as a high conversion. Methylation of 2-pyrrolidone could also be done with dimethyl carbonate, but then the selectivity for NMP was less (67%).

Introduction

In a world where fossil fuels will become scarce and therefore more and more expensive, it is important to look for alternative sources for chemical products. That is not only the case for transportation fuels, but also for industrial chemicals such as solvents and polymer precursors. One example of an industrial solvent that is currently based on fossil resources is *N*-methylpyrrolidone or NMP. NMP has high chemical and thermal stability making it suitable for a range of applications including the use as a solvent for plastics and as an ingredient in paint removers.[1] It has been reported that NMP is safe and without any acute harmful effects,[2] although there have been other reports of toxicity developing upon inhalation or oral exposure.[3]

The global annual production of NMP is estimated to be 100–150 kton.[3,4] From a commercial point of view, manufacturing this product from a biorefinery instead of from conventional petrochemical products is potentially worthwhile, because the production volume is large enough to consider investing in a new process. In a previous paper we showed that glutamic acid, which can be derived from waste streams from biofuel production, can be enzymatically decarboxylated to form γ-aminobutyric acid (GABA), in a process that we expect to be both technically and economically feasible.[5] GABA could then be an intermediate for the synthesis of a variety of nitrogen containing industrial chemicals, such as NMP.

Taking the large bioethanol production plant that the company Abengoa is currently building in the Port of Rotterdam in the Netherlands as an example, this plant will annually produce around 500 million litres of grain-based ethanol, resulting in 360 kton of the byproduct dried distiller's grains with solubles (DDGS).[6] Wheat DDGS can contain as much as 10 wt% glutamic acid,[7] resulting in a potential glutamic acid stream of 36 kton. If this would all be converted into NMP, it would result in an annual NMP production of 23 kton, a significant part of the world market. Once glutamic acid becomes available in large volumes from byproduct streams such as DDGS as opposed to the current production method of fermentation,[8] it will become less expensive. Then the production of NMP from glutamic acid could become an interesting process for chemical companies, if the process can be competitive with current production technology.

Scheme 1 shows the current and the proposed processes for the production of NMP. Currently NMP is made by reacting butyrolactone with methylamine, at high temperature (200–350 °C) and pressure (100 bar). Methylamine is a corrosive and highly flammable gas.[10] So if NMP could be made by methylation of 2-pyrrolidone, which is readily formed by the cyclization of GABA,[11] the NMP would become largely biomass based instead of fossil based, and its production process could become more energy-efficient, safer and dependent on fewer reagents. If the methylating agent would be biobased as well, NMP production would become fully biobased.

Traditional methylating agents, such as dimethyl sulfate and methyl iodide, are toxic and not environmentally friendly, because in their use stoichiometric amounts of waste salts are produced. In search of a better methylating agent, dimethyl carbonate (DMC, produced from methanol, oxygen and carbon monoxide) was shown to be capable of methylating various molecules and forming only methanol and CO_2 as side products.[12,13] In a reaction catalyzed by zeolites, DMC can methylate different phenols and amines.[14] Ben Taleb *et al.* showed that it is possible to use DMC to methylate amides, such as acetamide and several lactams (*e.g.* 2-pyrrolidone), with the quaternary ammonium salt cetyl trimethylammonium bromide (CTAB) as a catalyst.[15] Unfortunately, methanol did not show any methylating activity under these conditions (220 °C in an autoclave). To perform a methylation reaction with just methanol would be highly advantageous as only water is generated as a co-product and also the atom efficiency would be better than using DMC. Oku *et al.* showed that *N*-methylation of several amines with methanol is possible under supercritical conditions

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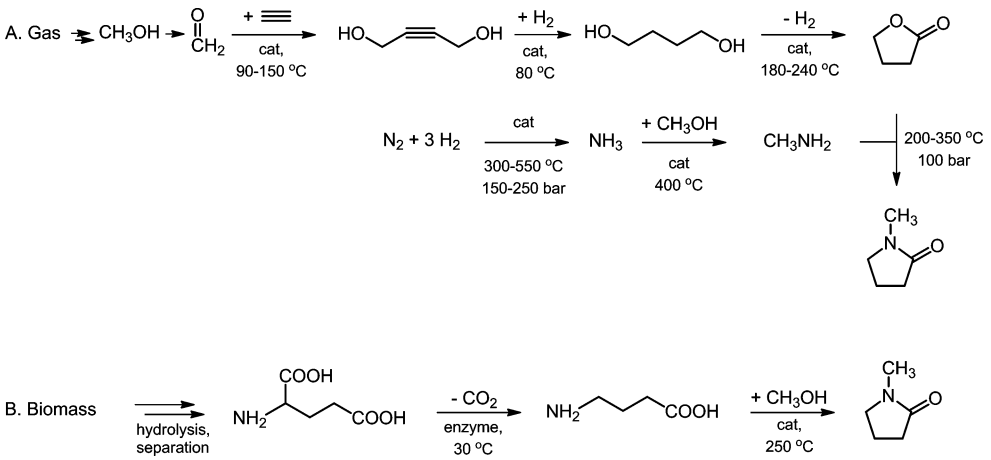


Scheme 1 Simplified overview of all process steps towards NMP. A: Fossil based;[9] B: Biomass based.

with a bifunctional acid–base catalyst.[16] A prerequisite for good conversion with their catalyst is an 'anchoring group' on the amine, such as an alcohol or another amine that can form a bond with the surface of the catalyst. Therefore the catalyst worked well for 2-aminoethanol, but resulted in a poor conversion with molecules such as aniline and 2-pyrrolidone. Other methylation reactions of lactams such as 2-pyrrolidone with methanol that are reported in literature were performed in the gas phase, at temperatures that are typically as high as 400 °C.[17]

The goal of this paper is to investigate the possibility to synthesize NMP from GABA, in order to obtain biobased NMP. We will show that it is possible to perform the cyclization of GABA and the subsequent catalytic methylation of 2-pyrrolidone with methanol in a one-pot procedure, under conditions that are milder than those of the current process for the production of NMP from butyrolactone, with a catalytic amount of an ammonium salt such as CTAB or ammonium bromide. We also investigated the possibility to use DMC in combination with a NaY zeolite catalyst to perform the methylation of 2-pyrrolidone. This will be compared with the use of methanol as a methylating agent.

Experimental

Materials and equipment

γ-Aminobutyric acid (Fisher, >99%), 2-pyrrolidone (Sigma, >99%), anhydrous methanol (Sigma, >99.8%), ammonium bromide (Sigma, >99%), ammonium chloride (Sigma, >99.5%), ammonium iodide (Fisher, >99%), cetyltrimethylammonium bromide (CTAB, Fisher, >99%), cesium bromide (Sigma, >99.5%), sodium bromide (Sigma, >99%), 1-butyl-3-methylimidazolium bromide (BMIM, Sigma, >98.5%), and methyltriphenylphosphonium bromide (MTPB, Sigma, >98%) were all used as received. Dimethyl carbonate (DMC, Sigma, >99%) was dried by refluxing over sodium sulfate and distilled under N_2 prior to use. NaY (CBV100, Zeolyst) was activated overnight at 70 °C under vacuum prior to use.

All reactions were performed in a Parr Series 5000 Multiple Reactor System, with six stainless steel autoclaves of 75 mL internal volume used in parallel.

High resolution MS spectra were recorded on an Exactive apparatus from Thermo Scientific, equipped with an ESI probe. Spectra were recorded both in positive and negative mode. *m/z* ratios were detected from 50 to 500.

GC-MS was performed with a Finnigan GC8000top apparatus connected to a Finnigan Automass II quadrupole EI-MS system. The used column was a BPX5 from SGE, 30 m x 0.25 mm x 0.25 μm. Helium carrier gas was applied at 100 kPa, the temperature program 50–300 °C at 10 °C min^{-1}. *m/z* ratios were detected from 35 to 500.

Methylation procedure with methanol

In a typical experiment, a glass liner was charged with ammonium bromide (59 mg, 0.60 mmol), 2-pyrrolidone (0.90 mL, 12 mmol) and methanol (3.0 mL, 74 mmol), and placed in an autoclave. Before reaction, the atmosphere in the autoclave was replaced with nitrogen by applying five vacuum-nitrogen cycles. Each reactor was heated to 250 °C in 20 min and left at 250 °C for five hours (the pressure in the reactor is then approximately 5 bar), after which heating was stopped and the reactor cooled to 100 °C in one hour and down to room temperature in five hours at which point the reactor was opened and the contents removed. Methanol was evaporated under reduced pressure and a crude sample was taken for determining the conversion and selectivity by ^{1}H-NMR (400 MHz). GC-MS and high resolution ESI-MS were further used to identify the formed products. No sampling was performed during the reaction, in order to avoid interference with the experiment. For purification, column chromatography was used with a 4 : 1 (vol.) mixture of chloroform and ether as the mobile phase. On TLC, the R_f values of NMP and 2-pyrrolidone with the same mobile phase were 0.2 and 0.1, respectively.

Methylation procedure with DMC

In a typical experiment, a glass liner was charged with NaY zeolite (0.50 g), 2-pyrrolidone (0.50 mL, 6.6 mmol), DMC (8 mL, 0.1 mol) and diglyme (0.20 ml, 1.4 mmol, internal standard) and placed in an autoclave. Before reaction, the atmosphere in the autoclave was replaced with nitrogen by applying five vacuum-nitrogen cycles. The reactors were heated to the required

temperature and kept at this temperature for the set amount of time, after which heating was stopped and the reactor cooled down to room temperature in about five hours at which point the reactor was opened and the contents removed. DMC was then evaporated under reduced pressure and a crude sample was taken for determining the conversion and selectivity by ^{1}H-NMR (400 MHz). Yield, conversion and selectivity were determined by comparison of the ^{1}H-NMR signal of diglyme with those of 2-pyrrolidone and NMP. GC-MS was further used to identify the formed products. No sampling was performed during the reaction, in order to avoid interference with the experiment.

Results and discussion

Catalyst screening

Ben Taleb *et al.* showed that CTAB can be used for the methylation of 2-pyrrolidone with DMC.[15] Here the use of different halogen salts as catalysts for the methylation of 2-pyrrolidone with methanol was investigated. This was done in order to determine the possibility to use CTAB as a catalyst, to investigate the possibility of using other halogen salts, and to obtain mechanistic information.

As can be seen in Fig. 1, bromide containing salts such as cetyl trimethylammonium bromide (CTAB), 1-butyl-3-methylimidazolium bromide ([Bmim]Br), methyltriphenyl-phosphonium bromide (MTPB) and ammonium bromide show an excellent ability to catalyze the methylation with methanol at 250 °C. Similar results were also achieved with ammonium bromide and ammonium iodide. Ammonium bromide was chosen as the preferred catalyst for further studies. Although it does not provide the highest conversion, it was chosen because it has the same high selectivity and is a readily available and inexpensive salt.

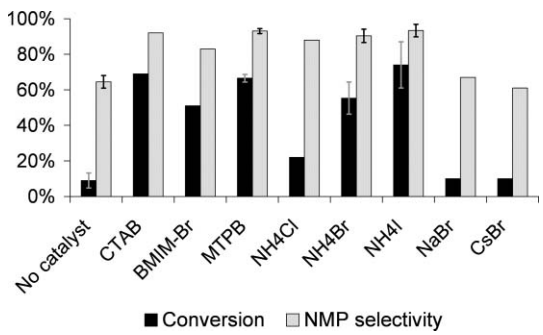
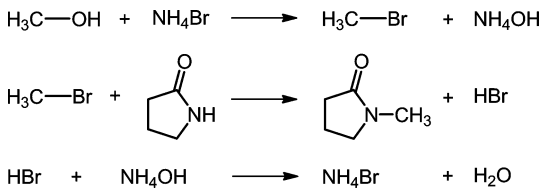


Fig. 1 Conversion and selectivity determined for the methylation of 2-pyrrolidone with methanol in the presence of different catalysts. Experiments were carried out with 0.6 mmol catalyst, 1.0 g (12 mmol) 2-pyrrolidone and 3.0 mL (74 mmol) methanol, at 250 °C, for 5 h.

Reaction mechanism

The fact that ammonium chloride is less active than ammonium bromide which in turn is less active than ammonium iodide (Fig. 1), leads us to believe that a halomethane is involved in the reaction sequence. In such a mechanism, the hydroxy group of methanol is replaced by a halide ion in an S_N2 reaction, which is easiest for a good nucleophile like iodide.[18] The proposed reaction sequence, shown in Scheme 2, is analogous to the one proposed for the methylation with DMC or methyl formate.[15]



Scheme 2 Proposed reaction sequence for the methylation of pyrrolidone. In this scheme, NH_4 can be substituted by any of the bromide salts.

As the selectivity is not 100%, the formation of side products was investigated. Five side products were identified by high resolution MS (Table 1): γ-hydroxybutyric acid (GHB), γ-hydroxybutyric acid methyl ester (MGHB), γ-butyrolactone (GBL), trimethylamine and tetramethylamine. The formation of these compounds was unexpected, as it means that the nitrogen atom from the lactam, which is a poor leaving group, has been replaced by oxygen. Scheme 3 shows a suggested reaction mechanism for the formation of these side products. Methylation of NMP would turn the nitrogen atom into a good leaving group, making the amide susceptible to a nucleophilic ring opening. Further methylation then yields a quaternary nitrogen that is eventually substituted by water, giving GHB and trimethylamine as products. GHB can cyclize to GBL, or react with methanol to form MGHB. Trimethylamine can be methylated to form a tetramethylammonium salt.

Strengthening the postulated reaction mechanism is that both the presence of GHB, MGHB and GBL were detected (by H-NMR and ESI-MS), and also the presence of trimethylamine and the tetramethylammonium salt (by ESI-MS). The latter two molecules could have been formed by methylation of ammonium bromide, but they were also detected when MTPB was used as catalyst. As MTPB contains no nitrogen, the methylated amines must originate from 2-pyrrolidone and are likely to be side products from the formation of GHB. Table 1 shows the exact masses and the anticipated products, from high resolution ESI-MS in both positive and negative mode.

Ammonium bromide catalyzed methylation

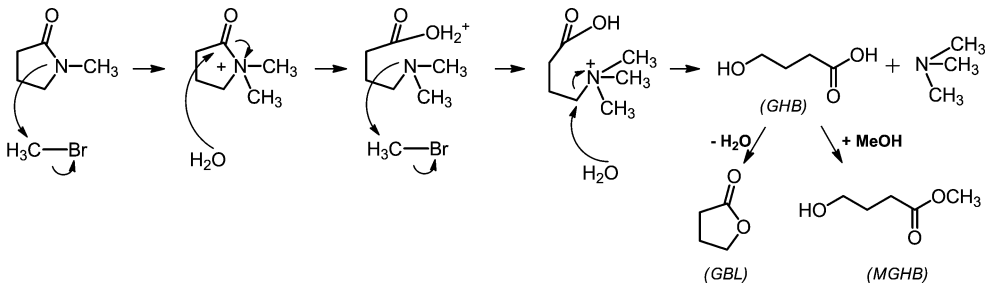
The influence of pressure and temperature on the conversion and selectivity of the reaction were studied with ammonium bromide as a catalyst, to determine the optimal reaction conditions. Our results showed that an increased pressure does not lead to a significant change in conversion, but does lead to a decrease in NMP selectivity (from >90% to 70%), due to the formation of more of the side products GHB, MGHB and GBL. The best pressure to perform this reaction was found to be 5 bar (obtained by starting with atmospheric pressure and heating the closed autoclave).

Fig. 2 shows that there is a temperature threshold value between 200 and 225 °C, from which the reaction rate increased dramatically. At very high temperatures the selectivity of the reaction decreases due to the formation of a black tar.

A study of conversion and selectivity in time (Fig. 3) shows that next to a high selectivity it is also possible to achieve high

Table 1 Measured *m*/*z* ratios with the molecular formula and the anticipated products

	m/*z*	Molecular formula (theoretical mass)	Derived compound
Positive mode	58.0656	C_3H_8N (58.0651)	Trimethylamine (–H)
	60.0812	$C_3H_{10}N$ (60.0808)	Trimethylamine (+H)
	74.0967	$C_4H_{12}N$ (74.0964)	Tetramethylammonium
	86.0602	C_4H_8ON (86.0600)	2-Pyrrolidone (+H)
	100.0759	$C_5H_{10}ON$ (100.0757)	*N*-Methylpyrrolidone (+H)
Negative mode	78.9178, 80.9157	Br (78.9178)	Bromide (2 isotopes)
	84.0444	C_4H_6ON (84.0444)	2-Pyrrolidone (–H)
	85.0284	$C_4H_5O_2$ (85.0284)	γ-Butyrolactone (–H)
	103.0390	$C_4H_7O_3$ (103.0390)	γ-Hydroxybutyric acid (–H)
	117.0574	$C_5H_9O_3$ (117.0546)	γ-Hydroxybutyric acid methyl ester (–H)
	126.9040	I (126.9039)	Iodide



Scheme 3 Suggested reaction mechanism for the formation of the side-product GHB from methylated 2-pyrrolidone. GHB may then react with methanol to form MGHB or cyclize to GBL.

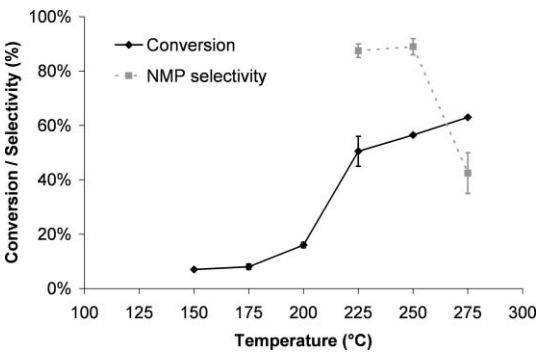


Fig. 2 Conversion and selectivity as a function of the reaction temperature. Experiments were carried out with 59 mg NH_4Br, 1.0 g 2-pyrrolidone and 3.0 mL methanol, for 5 h. Error margins indicate the differences between two duplicate experiments. Selectivity at low temperature could not be accurately determined because of the low conversion.

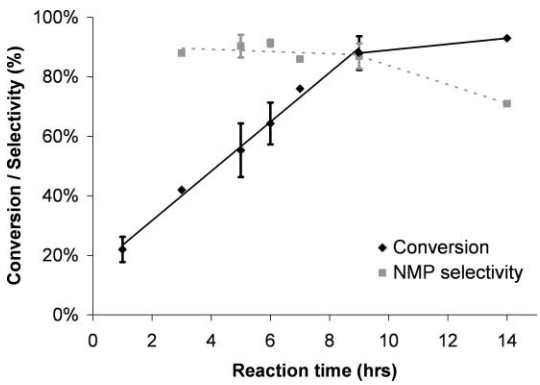


Fig. 3 Conversion and selectivity as a function of the reaction time. Experiments were carried out with 59 mg NH_4Br, 1.0 g 2-pyrrolidone and 3.0 mL methanol, at 250 °C. Error margins indicate the standard deviation between two or three identical experiments. Fitting the data points from 1 to 9 h to a linear function gives an R^2 value of 0.99.

conversions, by allowing the reaction to proceed for a longer period of time. After nine hours, the conversion achieved is 88 ± 6% and the corresponding selectivity 87 ± 4%. While it is possible to obtain high conversions with this reaction, the employed reaction time in our studies is five hours, as it offers a high selectivity in combination with a medium conversion, making it possible to study how other factors such as the reaction temperature can influence the conversion.

An isolated yield of 57 mol% NMP was obtained after purification of the product of a five-hour experiment at 250 °C by column chromatography, which is consistent with the data shown in Fig. 3.

Scope of the alkylation

To investigate the scope of the alkylation reaction, it was also performed with other, more sterically hindered alcohols. Chosen for this were: ethanol, *n*-propanol, *n*-butanol, 2-butanol, *t*-butanol and benzyl alcohol. The results are shown in Table 2. For the sake of comparison, the ratios (determined by ^{1}H-NMR without evaporating the alcohol) between 2-pyrrolidone and the *N*-alkylated pyrrolidone (NAP) are shown, which are a good indication of the reaction progress after five hours.

These results show that methanol is more reactive than ethanol, *n*-propanol and *n*-butanol. This is probably related to the initial substitution of the alcohol with bromide, which proceeds more readily when it is less sterically hindered. In

Table 2 *N*-alkylation of 2-pyrrolidone, with different alcohols. Shown here is the ratio between 2-pyrrolidone and *N*-alkylated pyrrolidone (NAP) in the crude reaction mixture, after 5 h reaction time. Experiments were carried out with 59 mg NH4Br, 1.0 g 2-pyrrolidone and 72 mmol alcohol, at 250 °C. Error margins indicate the variation between two identical experiments

	NAP/Pyrrolidone (mol/mol)
Methanol	1.2 ± 0.3
Ethanol	0.15 ± 0.03
n-Propanol	0.07 ± 0.01
n-Butanol	0.16 ± 0.02
2-Butanol	0
t-Butanol	0
Benzyl alcohol	1.4 ± 0.1

between ethanol, *n*-propanol and *n*-butanol, no trend could be observed. 2- and *t*-butanol yielded no alkylated product. In their case, elimination of the alcohol probably took place instead of bromination, leading to the formation of gaseous (iso)butene, as an increase of pressure (from 3 to 7 bar) was observed during the reaction. Another indication for the formation of butenes was that after the reaction, 2- and *t*-butanol had been partially consumed in the reaction mixture. In the case of benzyl alcohol, *N*-benzylpyrrolidone was formed at a similar rate as *N*-methylpyrrolidone. In this case the mechanism can be S_N2 or S_N1, because it is well known that adjacent π-bonds enhance both mechanisms.

One-pot cyclization and methylation of GABA

From literature, it is known that GABA can cyclize rather easily, for example in boiling toluene, catalyzed by silica using a soxhlet set-up for water removal.[11] Therefore our hypothesis was that it should be possible to cyclize and subsequently methylate GABA in a simple one-pot procedure, in order to obtain biobased NMP. Fig. 4 shows that upon heating GABA in methanol without added catalyst, 2-pyrrolidone is indeed obtained in a high yield, even without water removal. When GABA was heated in methanol with ammonium bromide present, there was only 2 mol% GABA left after five hours at 250 °C and the subsequent conversion of 2-pyrrolidone was 42 mol%, with a selectivity for NMP of 92%. This means that it is actually quite straightforward to convert GABA to NMP in a one-pot procedure, with methanol and a catalytic amount (5 mol%) of ammonium bromide. Fig. 4 also shows that when starting with NMP, 99% of it was recovered, indicating that NMP is stable

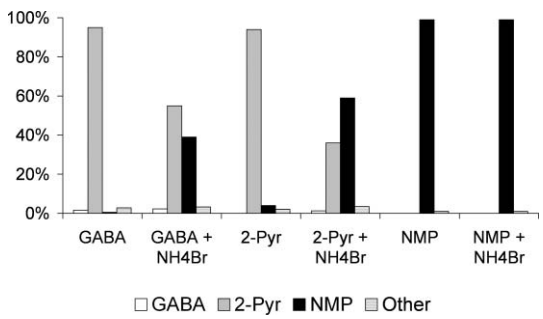


Fig. 4 Molar ratio of the products present in the reaction mixture after 5 h at 250 °C, when starting with different materials, in the presence and absence of NH_4Br catalyst. Determined by ^{1}H-NMR.

under the applied conditions. However, when the reaction was performed at an increased pressure, NMP became unstable with ammonium bromide present and formed 17 mol% of the GHB-related side products (data not shown), which is in accordance with the postulated mechanism in Scheme 3.

Process design

In an industrial process design, the removal of water from the reactor could be incorporated in a continuous process, together with continuous product removal by vacuum distillation. 2-Pyrrolidone and NMP are easily separable by distillation (their boiling points at 1 atm are 245 and 202 °C, respectively), so one could think of a product stream continuously leaving the reactor, passing through a water absorber (for example a zeolite drier) into a first distillation column for the removal of the excess of methanol and then into a second distillation column, where the top fraction would be NMP and the bottom fraction, 2-pyrrolidone, could be either isolated as a co-product, or could be recycled to the reactor. Schematically this process is shown in Fig. 5. What should be considered is the fate of the catalyst. As the salt is a homogeneous catalyst, part of it will be removed from the reactor with the product removal and will end up in the rest of the process. A part will probably stay in the zeolite dryer where it may be recovered and the rest will end up in the 2-pyrrolidone stream and can directly be recycled to the reactor. When warm 2-pyrrolidone is recycled, ammonium bromide will stay in solution, but it could also be cooled to room temperature at which point the ammonium bromide is sparingly soluble in 2-pyrrolidone and could be filtered off to a large extent.

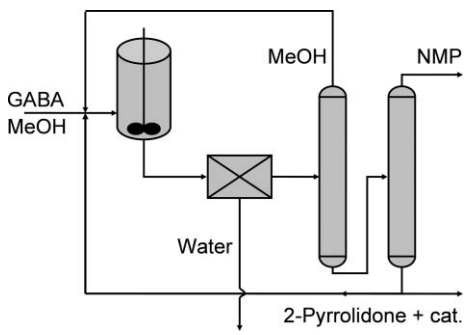


Fig. 5 Process scheme for the continuous production of NMP from GABA and methanol.

Comparison with DMC as methylating agent

Although the atom efficiency of the above described process is relatively high (73%), the use of a homogeneous halogen-based catalyst may be perceived as a drawback in a commercial application, for there is the risk of product contamination with traces of bromide. Oku *et al.* reported an acid–base bifunctional zeolite that catalyzes methylation reactions with supercritical methanol, but for 2-pyrrolidone the conversion was quite poor.[16] As was discussed in the introduction, DMC is a versatile methylating agent, also in combination with heterogeneous catalysts such as NaY zeolite.[12–14] However, to our knowledge there is no report of the use of DMC for the methylation of a (cyclic) amide, in combination with a heterogeneous catalyst.

Table 3 Results of *N*-methylation procedure with DMC, in the presence and absence of NaY

Temp/°C	Catalyst	Time/min	2-Pyrrolidone Conversion (mol%)	NMP Selectivity (mol%)	NMP Yield (mol%)
130	—	60	8	0	0
130	NaY	120	7	0	0
130	NaY	240	5	0	0
180	—	60	76	4	3
180	NaY	60	81	17	14
180	NaY	240	84	23	19
250	—	60	90	48	43
250	NaY	30	86	66	57
250	NaY	60	85	67	57

Therefore we attempted the methylation of 2-pyrrolidone with this reagent, in the presence of NaY zeolite. The results, shown in Table 3, indicate that it is also possible to methylate 2-pyrrolidone with DMC. At a temperature of 250 °C, a maximum NMP yield of 57 mol% was obtained after 30–60 min of reaction. The results show that a high temperature is needed for the *N*-methylation of 2-pyrrolidone with DMC, because at 180 °C the NMP yield goes down while the conversion of 2-pyrrolidone remains the same, indicating that the selectivity towards NMP goes down, and at 130 °C 2-pyrrolidone is hardly converted. At lower temperatures (130 and 180 °C), we found that 2-pyrrolidone is partly *N*-methoxycarbonylated instead of *N*-methylated. This is in line with previous reports by Selva *et al.*, who indicated that at a lower temperature DMC acts as a methoxycarbonylating agent and at higher temperatures as a methylating agent, although there is not always a clear cut-off at which temperature each reactions occurs.[12]

Both at 180 and 250 °C, the results indicate that NaY has a directive effect towards the methylation reaction, because the selectivity towards NMP formation increases with the zeolite present, although this effect is not large.

When comparing these results with the results that were obtained with the methylation procedure with methanol, they seem rather poor. Although the DMC reaction is quicker, both the atom efficiency (51%) and the achieved selectivity (67%) with DMC are less than with methanol, which leads to the conclusion that the methanol procedure is preferable over the DMC procedure.

Conclusion

The goal of this paper was to investigate the possibility to synthesize NMP from GABA, that can be obtained by the α-decarboxylation of glutamic acid.[5] In this way NMP could be made largely biobased, and with the use of a biobased methylating agent (for example biomethanol[19]) NMP would become fully biobased.

The synthesis of NMP from GABA was done in two steps, the first being the cyclization of GABA to form 2-pyrrolidone, and the second the *N*-methylation of 2-pyrrolidone to form NMP. We found that this is possible in a one-pot procedure, where the methylation reaction can be performed with methanol as the methylating agent, catalyzed by a halogen salt such as ammonium bromide, ammonium iodide or CTAB. The selectivity that was achieved for this reaction is greater than 90%, although we found that at an increased pressure the selectivity towards NMP goes down.

The methylation of 2-pyrrolidone can also be done with DMC in the presence of NaY zeolite. However, the selectivity that was found for this methylation procedure (67%) was significantly less than that of the methylation with methanol and a halogen salt catalyst. Combining this with the lower atom efficiency in the use of DMC, the preferred method of methylation would be the procedure with methanol.

This paper shows that there is now a straight-forward route to synthesize biobased NMP, based on glutamic acid. This can be done by combining the enzymatic decarboxylation of glutamic acid to form GABA with the one-pot cyclization and methylation of GABA to form NMP.

Acknowledgements

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