Thesis Biobased Chemistry and Technology

Development of a capstone project

- as part of the micromaster "Biobased sciences for sustainability"

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Abstract

Recently the first massive open online courses (MOOCs) of the micromaster 'Biobased Sciences for Sustainability' started. This new online micromaster programme of five courses has to be completed with a final project, a so-called capstone project. This is the first micromaster and therefore the first capstone that had to be developed by Wageningen University. The goal was to develop a capstone project in which high-order thinking skills are assessed and where the knowledge of the different MOOCs within the micromaster 'Biobased Sciences for Sustainability' are integrated.

The capstone project was developed according to the ADDIE framework. Using relevant literature and the 'four component instructional design' (4C/ID) model, considerations for the content of the capstone were made. The goal of the capstone was that students are able to evaluate and design a biobased process. Therefore, first the final assignment was developed by Harry. In order to analyse what students should learn in the whole capstone, this final assignment was made from a student perspective. The findings from this analysis, together with information found in literature, showed that interaction and guidance for students seemed the most important aspect for development of the capstone. Keeping these aspects and the 4C/ID model in mind, a design for the capstone was made.

Eventually, a complete capstone, where the different MOOCs were integrated and higher-order thinking skills could be assessed, was developed. The material made can be used for implementation of the first capstone from Wageningen University in the online platform Edx.

Contents

1. Introduction

Recently the first courses of the online programme 'Biobased Sciences for Sustainability' have started. The first online students are following these courses of the so-called micromaster: a programme of multiple 'massive open online courses' (MOOCs) with a level of education comparable to a Master programme. All these MOOCs consist of short educational videos, informational texts, quizzes and assignments. Every MOOC has its own exam which is graded. Besides these exams, a final capstone will be implemented to complete this micromaster.

A capstone is defined by the online platform Edx as a project or exam that can be used to complete a micromaster. In this case the capstone will be used both as assignments for integration of different MOOCs and as a final assignment, which will be graded. This micromaster is the first micromaster developed by Wageningen University. Therefore, there is no experience in developing a capstone within Wageningen University.

The micromaster consists of 5 different MOOCs and the capstone, covering 24 ECTS. Students who successfully complete this micromaster are allowed to apply for the on-campus master programme 'Biobased Sciences' at the Wageningen University. After passing an entrance exam, these students also get the opportunity to complete this micromaster programme with the remaining 96 ECTS on-campus. So it should be possible to complete this on-campus programme in 1.5 year instead of 2 years. Therefore, it is important to reach the same level of education for online students as for the students on-campus.

Students, of both online and on-campus education, are expected to have certain knowledge, skills and attitudes to eventually be able to evaluate and design a sustainable biobased process. These are so called 'higher-order thinking skills' which go beyond remembering and the understanding of knowledge. The challenge is to design a capstone in which the knowledge and skills of different MOOCs are integrated and higher-order thinking skills are assessed.

Normally these kind of higher-order thinking skills are guided by teachers. On-campus, teachers can influence in the process students are going through. Also in on-campus education students could work in a group and get support from each other. In online education, where in this case students work self-paced and individually, this form of influence and support is hard to achieve. This leads to the search for other ways to guide students and a way of assessing higher-order thinking skills.

The focus of the capstone project will be on the MOOC *advanced biobased conversion*. Since the content of the online and on-campus education should be the same for all students, the content of the micromaster could be compared to the on-campus courses. The on-campus equivalent of this MOOC is the course *conversions* *in biobased sciences*. In this on-campus course students will write an advice about a biobased process. The students investigate which (bio)chemical method is suitable for a certain process and consider important process strategies. Students will work together in groups and get guidance of a teacher. Before a final advice is written and handed in, a teacher can help students with problems they encounter or adjust the way of writing for example. A similar kind of assignment can be given to online students in the capstone, but the obstacle here would be how this guidance should be achieved.

2. Objective

The goal is to develop a capstone project in which high-order thinking skills are assessed and where the different MOOCs within the micromaster ‘Biobased Sciences for Sustainability’ are integrated.

This results in the following questions:

- What are the requirements for a ‘good’ capstone?
    - What are essential differences in online and on-campus education in terms of student guidance for the development of a capstone?
    - How to assess high-order thinking skills in online education?
    - How to integrate aspects of different MOOCs in one project?
- How to make a capstone?
    - What are the possibilities and restrictions of the online platform Edx?

3. Approach

In order to answer the questions, first literature is reviewed for information about online learning with respect to higher-order thinking skills and student guidance. Next more knowledge about the four component instructional design (4C/ID) model is gathered. This model is used as an instrument to develop assignments for the capstone project.

Starting point for the development of the capstone was on the one hand (the lay-out of) the MOOCs and on the other hand the final assignment of the capstone developed by Harry Bitter (appendix A). Content of the MOOCs is developed parallel to the development of the capstone, so partly only outlines are used.

First the final assessment was performed from a student's perspective (appendix B) in order to serve as an example and indicate points of attention for the capstone development. Secondly, the results of this assignment were discussed and improvements for online guidance were indicated. Together with these findings and the use of the 4C/ID model finally the assignments for the capstone were developed.

Since the main focus of the capstone is about (bio)chemical conversion in a biobased process, the corresponding course given to on-campus students was also used for identifying points of attention for assignment development. Due to time limitations, these findings are only listed and suggestions are made, but these are not integrated in suggested assignments.

4. Background information

New educational materials can be made using a general model of five phases, analysis, design, development, implementation and evaluation, abbreviated with ADDIE. Since ADDIE only represents a framework and gives no clear guidelines for development, a development strategy is needed. For the concrete development of a capstone the four component instructional design (4C/ID) model was used. Furthermore, literature is reviewed to get more insight in online education. A brief overview of relevant information is given in this chapter.

4.1 ADDIE model

In general, a typical way of developing and using new instructional materials is using the ADDIE model. This framework consists of several phases: analysis, design, development, implementation and evaluation. In the analysis phase all the information about the learner, content, context and gaps is gathered to be able to make suitable instructional materials. With all this information, learning outcomes can be formulated and the outline of the materials can be designed. In the development phase all the details for the designed materials are developed. These new materials can be tested, distributed and executed in the implementation phase and eventually evaluated in the evaluation phase (Morrisoon et al., 2013; Peterson, 2003). As a result from the last phase it is possible to redo some of the earlier phases in order to improve the made materials. These phases do not necessarily have to be executed in this order or fully finished before the other is started (Morrisoon et al., 2013). In this project mainly analysis and design will be performed with eventually the development of a capstone. The implementation and evaluation phase will not be performed.

4.2 Four component instructional design model

The 4C/ID model is used to develop educational material for a training, education or course for example, in which a complex skill is learned. Learning a complex skill involves integrating knowledge, skills and attitudes and coordinating different so-called constituent skills. These constituent skills consider the underlying, smaller skills in order to reach the overall complex skill (Van Merrienboer and Kirschner, 2012). It is said that learning a complex skill is more than the sum of its individual parts, which means that complex skills have to be learnt within the complete skill (van Merrienboer et al., 2002). Often this complex learning also considers the transferring of what is learned by education to daily life or a work setting (Van Merrienboer and Kirschner, 2012).

The 4C/ID model seems suitable for several reasons. Since the goal for students in the capstone project is to be able to evaluate and design a biobased process, this can be considered a complex skill. There are sub-skills that make up the overall skill of evaluating and designing a biobased process. Subsequently the 4C/ID model is ideally used for skills used in real life. So for example skills that are directly used in a working setting. This could also be the case for evaluating and designing a biobased process. Furthermore, this model consists of several steps and makes it possible to see what is suitable or not, since this project considers online learning, which is not the setting where instructional models are designed for in general.

The four components of the model refer to the learning tasks, supportive information, just-in-time information and part-task practice which together make complex learning possible. These learning tasks include tasks which covers the whole skill. These tasks can vary in complexity, but should always represent the whole skill in an authentic way. For some parts doing more exercises could be preferred, which is covered by part-task practice. This could be preferable for recurrent constituent skills that should be performed automatically or flawless. Supportive information is available for every set of tasks and concerns typically textbook information. The representation can vary, but this information is necessary in general to be able to perform the learning tasks. Specific details or help for a specific task is provided in well timed, just-in-time information. Together with several analyses necessary to develop these components, a ten step approach to complex learning is made as a guide (Van Merrienboer and Kirschner, 2012).

4.3 Online versus on-campus education

For this project it is interesting to know what the essential differences are between online and on-campus education. Since the goal is to develop a capstone and students will not learn new content in this capstone, the comparison focuses on differences in student guidance and assessment of higher-order thinking skills. The development of capstones is a rather new concept. There is no literature available about development of capstones in an online environment and literature on development of MOOCs is very limited, therefore literature is used concerning online education in general.

4.3.1 Learning outcome

MOOCs are a relatively new way of providing online courses, but online education in general is not a new concept. Many research has been performed in the last two decades to investigate whether online education is comparable with face-to-face education. For example, a study comparing midterm exams scores of online and traditional students at the Stevens Institute of Technology revealed little or no differences in student learning outcomes (Fallah and Ubell, 2000). There are many more examples like these that show little or no differences in learning outcome between online and traditional education. For example, education for a MBA class showed no difference in learning outcome (Arbaugh, 2000) Also an example of distance learning for a nursing course showed that both kinds of students performed equally (Blakeley and Curran-Smith, 1998). Using online learning for virtual role simulations in buisness subject resulted in comparable student outcome for online and on-campus students (Freeman and Capper, 1999). There is also evidence of worse learning outcomes in an online environment, but according to Swan et al. (Swan, 2003) these outcomes are a minority of all research conducted.

Still it is hard to say what makes online education successful. All the evidence found, for successful as well as less successful online education, is mostly based on examples. It is hard to say which indicators make an online course successful and whether or not all these situations are comparable. Even a more recent study, which had a quantitative approach, showed no significant difference in the two studied groups of online and on-campus students for the same course of applied physics (Stöhr et al., 2016).

An overview is made of research presenting 'no significant difference' between online ways of education and traditional education (Russell, 1999) and this overview has been growing since (2010). In other research (Swan, 2003), the question arose what is behind this 'no significant difference' and what the practical implications are for successful online education. It is stated that the key for successful online education is the attention for the student's interaction. This means interaction with the content, with teachers and with other students. A list of practical implications is made based on all the gathered research findings. Some interesting findings for this project concern the presence of teachers in discussions or individual feedback of teachers to students. These practical implications contribute to successful online education (Swan, 2003).

4.3.2 Essential differences

Even though there is no significant difference in student learning outcomes, there are differences in the way education can be designed. The most obvious difference in online and traditional on-campus education is the lack of face-to-face interaction in an online environment. Also research among online students suggests that support for students' interaction with teachers, content and other students deserves special attention in the course development (Swan, 2010).

Another aspect is the difference in time and space. Asynchronous online learning makes education available for everyone that is interested, at any time. This makes interaction even harder, as students can choose their own pace. In on-campus education all students have access to the same education at the same time. Most of the online courses have a certain amount of freedom to choose at which pace a course is taken. This interferes with a potential discussion or group work, which is usually used in on-campus education (Kellogg, 2013). The use of an online discussion board can be a good way to enhance learning for online students. A discussion board has to be managed by a teacher, but is still a good addition (Kellogg, 2013). So, interaction is at the centre of attention for successful online education.

4.3.3 Higher-order thinking skills

In the capstone project higher-order thinking skills are required to reach the overall goal of the capstone and these skills also have to be assessed at the end. The definition of higher-order thinking skills is based on a taxonomy about learning. The best known one is Bloom's taxonomy. In this taxonomy several classes of learning are distinguished as can be seen in figure 1. The first, lower classes are used in getting and understanding knowledge. The higher classes are necessary to create new knowledge, such as analysing, evaluating or creating of knowledge (Krathwohl, 2002). These are called higher-order thinking skills.

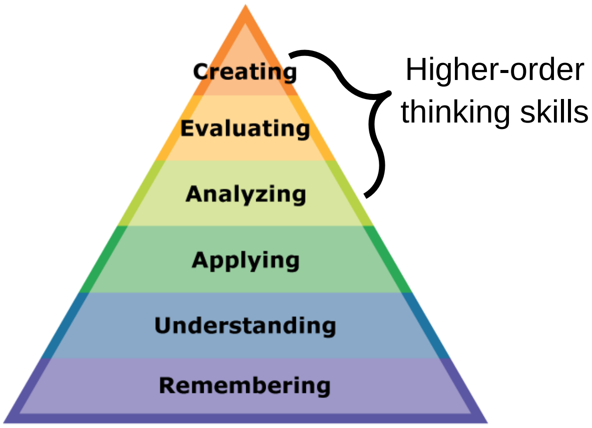

Figure 1: Bloom's revised taxonomy. The upper three classes are the so-called higher-order thinking skills. Figure adapted from (Coffey)

In on-campus education at Wageningen University, higher-order thinking skills are mostly stimulated and assessed by exams with open ended questions, reports, presentations and discussions. In an online setting, it should still be possible to stimulate and assess higher-order thinking skills by the same methods, but the practical implementation will have to be changed. A study on a graduate course in applied physics, mentioned earlier, which compared student performance, also concluded that higher-order thinking skills are not triggered by video lectures, even when combined with quizzes (Stöhr et al., 2016). Their suggestion is to complement these learning activities with other learning activities in order to engage students in higher-order thinking skills. At Wageningen University lectures are also complemented with other learning activities. This supports the idea that the kind of learning activities used in on-campus education could be comparable in online education.

For this capstone project the final assignment concerns writing a report. The final report will be graded by a teacher. In that way the assessment of these higher-order thinking skills could be the same as for on-campus education. The difficult part is to stimulate these higher-order thinking skills and facilitating students to show and use these higher-order thinking skills.

Literature concerning higher-order thinking skills in online education is focused on the effects of the use of discussion fora to stimulate higher-order thinking skills. In these discussion fora evidence is found for higher-order thinking skills (McLoughlin and Mynard, 2009; Meyer, 2003). Furthermore, it has been found that a contribution of a teacher is necessary to stimulate these skills (Meyer, 2003). So, in online education higher-order thinking skills can be stimulated by the use of discussion fora, but a teacher is still necessary. Other ways of stimulating higher-order thinking skills in online education could be possible, but no evidence is found in literature.

4.3.4 Future perspective

Development of MOOCs is relatively new, therefore literature on development of MOOCs, or capstones, is limited. In September 2015 an international initiative is started to review the quality of MOOCs on a large scale, called MOOQ. The mission of MOOQ is “to develop a quality reference framework for the adoption, the design, the delivery and the evaluation of MOOCs in order to empower MOOC providers for the benefit of the learners” (2017). Unfortunately, this research is still being conducted and no results are available yet.

The coordinator of this research is the Open University of The Netherlands. At the Open University research about the student interaction in MOOCs is conducted. Their preliminary findings show that student-teacher interaction is rather low and there was only formative assessment and feedback from peers or the system, but not from any teacher. So special attention should be paid to student-teacher interaction. An important note for this research is the sample size of five different MOOCs (Kasch et al., 2016).

Since the offer of MOOCs is rapidly growing, more information about development and quality of MOOCs can be gathered. So hopefully in the near future more insight in how to develop MOOCs, and especially capstones, is gained.

5. Results and discussion

As described earlier, making new educational material can be done within the ADDIE framework. All the steps taken and corresponding results will be discussed for the relevant phases.

5.1 Analysis

In order to start the design of assignments for the capstone, it should be clear which content and which level should be covered by the capstone. The starting level of the online students is formed by the five MOOCs they already completed when starting the capstone. Part of these MOOCs are already available online, these MOOCs are studied globally by Iris. Other MOOCs are still in development and only some outline or draft versions were available. The information of these MOOCs are used to get a better overview of the course content and the way of working in MOOCs of Wageningen University.

The end level of the online students will be assessed by a final assignment in which students write an advice for a certain process. This final assignment will be graded and is made by Harry (Appendix A). Students have to give an advice how a deoxygenation reaction should be performed on an industrial scale considering different types of conversion methods. This represents the overall learning goal for students to be able to design and evaluate a biobased process, corresponding with the learning goals of the capstone.

5.1.1 Students' perspective

It is important to analyse what students have to learn in order to reach the overall goal. Ideally the designer is also an expert in the field or an expert can be consulted (Morrisoon et al., 2013). The latter one is the only option is this case. Therefore, Harry, as a teacher in this field, has made the final assignment. Normally a task analysis, together with the expert, is performed to determine what students already know and what they need to learn (Morrisoon et al., 2013). A task analysis can be quite time-consuming, since the expert ideally performs the task, so the designer can determine the different steps taken and asks questions (Militello and Hutton, 1998). As an alternative way of identifying what students should learn, Iris made the final assignment from a student's perspective. This method also gives a good insight in which guidance is necessary. As explained in chapter 4.3, interaction is very important in learning and an aspect that has to be considered differently from on-campus education. Since this interaction and student guidance is an important aspect for this capstone development, this method is chosen.

In order to get the most realistic outcome of this assignment, information is gathered from freely accessible sources by Iris. In the final assignment three journal articles were mentioned, which are also used in the report. As a student, Iris could serve as an example of an online student, because of her chemical knowledge, but without specific knowledge about biobased processes. It is assumed that most of the online students taking the whole micromaster have a certain amount of relevant chemical or (bio)technological background.

First, information about all the indicated aspects in the final assignment was gathered. With a summary of this information Harry was consulted in order to check if some aspects were missing and enough details were mentioned. With his feedback some more information was gathered on the possible catalysts and the report was written and handed in. The report (Appendix B) was discussed with Harry and resulted in some interesting findings.

One of the most important findings was the slight misinterpretation of the goal of the report. The focus of the report was not about the conversion methods, as intended, but more the whole process of creating a new biofuel. This could be solved with a more precise description of the goal of the final assignment. Another finding was the style of writing. Harry remarked a quite descriptive style of writing. Writing styles are more subjective than for example a clear description of the goal, but some guidance in this process could help. An example of a concluding advice or assignments to make this clear could be an option. Finally, another finding was the level of detail that was presented in the report of Iris. Some details, mostly about catalysis, were missed by Harry. This could be attributed to two different aspects. On the one hand freely accessible information is quite limiting in details of specific processes and catalysts. On the other hand it is hard to determine as a student what is expected when important concepts, which will be explained in the MOOCs, are not clear due to the fact that these MOOCs are still in development. This last problem is solved when online students will start with the capstone. The risk of lack of information can be reduced by giving some important information or ask for these details. Since it is the goal to let students come up with possible processes themselves, giving or asking all the necessary information is not favourable.

The overall finding from a student perspective is the need to know what is expected. If a student designs a biobased process for the first time, it is not clear what is expected as report. This is the moment where a student on-campus would consult a teacher to ask for these expectations or ask for feedback about a first draft version. It has to be noted that Iris is already used to write reports in general, which is not necessarily true for all online students. This could increase the need to know what is expected in terms of details and way of writing. So more attention should be paid to clarify the expectations.

5.1.2 On-campus perspective

During the development of the capstone, the on-campus course *advanced biobased conversion* was given. Since the students of this on-campus course got the same assignment as the final assignment of the capstone, these students were observed. In this on-campus course students were divided into two groups to make their advice report. Iris observed the meetings with Harry of the group working on the same assignment as will be used in the capstone. This was done to see what kind of questions students could ask and which guidance is given by a teacher in this assignment.

The students had two meetings and one mail conversation about this assignment. Their questions mainly concerned confirmation of their reasoning and level of details. The students wanted to know if they gave enough arguments and details to choose or discard a certain option they found. A minority of the questions concerned details about a specific reaction or feedstock used. Furthermore, Harry explained once again the focus on conversion and indicated that there any suggestions could be a correct one, as long as choices have a proper explanation.

Due to time restrictions, these findings could not be integrated in the design of the capstone. Most questions could be reduced with more clarification of what is expected, as described in earlier findings. Questions about found literature or specific processes are hard to prevent, since it is not known what students come up with. So these findings are not integrated, but correspond to earlier findings.

5.2 Design

Considering all these findings together, managing the expectations of students is the most important aspect for design of the capstone. These expectations consider the details of the assignment itself, the kind of information and amount of details that should be searched for and how this advice should be written and presented. If these expectations are clear, the need for guidance as a student also should be reduced.

The most straightforward option to manage the expectations of students is to give them an example of an advice about a process similar to the one of the final assignment, but this is not favourable. In this way there is still no link made between the different MOOCs and the final assignment. More important is the fact that by giving a very similar example not so much the intended skill is assessed, but rather the skill to copy and adjust a given advice. So options to involve different MOOCs and manage expectations without giving everything away were explored. As described in the findings for this development, this will be performed for three different goals: expectations considering the course content, considering giving an advice and guiding the final assignment.

5.2.1 Course content related design

First, relevant knowledge of the previous complete MOOCs should be refreshed. This is important, because it could be a way to focus on the subjects relevant for the final assignment and help to see the connections between different MOOCs and subjects. Since online students work self-paced, the first followed MOOC could be a long time ago and refreshing knowledge could be necessary. A good way to do so, is to develop questions which point out all the relevant concepts. This could be questions about a catalyst or reactor which names some important concepts as catalyst selectivity or reactor types for example.

In light of the 4C/ID model and the goal to close the gap between MOOCs and the final assignment, these questions should be authentic and in the light of the whole skill. Only a question about a catalyst gives no direction about how to consider this information in the context of a biobased process. So questions are made with examples of a complete advice. The information given with these questions gives relevant insights about what this information could mean for comparing different conversion methods.

5.2.2 Giving an advice related design

Next, some more insight in the way the report should be written should be generated. This can be described in an instruction for writing, but this has some drawbacks. Learning can be performed in many ways, but just reading something is not a powerful way of learning. It is better to exercise this in some way before writing an advice. Next to that it is not favourable to give this all away, because the students should have freedom to come up with their own ideas. If it is completely stated what should be written, this could hamper that freedom.

Exercising the way an advice can be written, can be reached in the same way as mentioned previously. So using questions to guide a student to consider given options and giving insight into how an advice should be written. Also in this case a realistic case which considers the whole skill will be used. For example, questions about comparing costs of given methods or which of the given methods has the best performance. This is preferably done for the same cases, so the link between used content and giving advice can be made easily.

5.2.3 Final assignment related design

After assignments about the content and the way of giving an advice, students should be able to start with the final assignment. As stated during the analysis phase, the final assignment can be more precise in describing the goal of the assignment, in order to make sure students completely understand the goal. But some more guidance could be preferable as well.

In the final assignment already some aspects about the content are listed. To make sure also some guidance in writing the report is given, a similar checklist for components of a report can be made. For example, to remind students that sources should be mentioned properly and there should be an introduction. Also an indication of the length of the report is given, to indicate that options should be explained extensively.

Furthermore, students can learn from each other. Higher-order thinking skills are triggered by giving something to think about. Thereby, as stated before, interaction among students is also important. So a way of interaction between students in this assignment can be useful and valuable. One way to achieve this interaction, is by using a way of peer-review where students can give each other feedback in order to give students the opportunity to make improvements.

Finally, the improved report should be handed in and will be graded by a teacher. Other options could be to use self-assessment or peer-assessment for the grading of the report. In these cases, a rubric should be provided to guide the students in grading a report. A big disadvantage of self- or peer-assessment is the variation among students that can lead to differences in grading. Since this report considers higher-order thinking skills which have to be assessed, it is hard to make sure students apply the same standard. Even if a rubric is used, this is hard to reach. In this final assignment there is no right or wrong answer and a student does not necessarily know if everything stated is correct. This makes fair grading by students among all students hard to achieve. Next to this, if students want to apply for the on-campus programme with a completed micromaster, the evaluation of the level of the student should be reliable. So the final assignment should be graded by a teacher.

5.3 Development

The complete result and details of the developed materials can be found in appendix D and appendix E. Before these materials were made, the possibilities in the online platform Edx were explored. The overview of these possibilities is given in appendix C. Here the considerations will be discussed for the same categories as before: development related to course content, giving an advice and the final assignment.

5.3.1 Course content related development

As can be seen in appendix D, multiple choice questions are made to refresh and focus the course content. All the questions are a form of multiple choice, because it is easier to give the student feedback to help them to refresh their knowledge. For open ended questions, someone has to check those answers, such as the student themselves, other students or the teacher. Now feedback is universal and immediately after answering, which is beneficial at this stage of refreshing.

As discussed earlier, these questions are in the light of the whole skill with using an example of an advice. This report is written by students for an on-campus course. In that course the assignment was to compare two given methods. As discussed in the design section, this report should not be completely the same as the report for the final assignment should be. This report considers a comparison for a chemical and biological conversion method, but does not consider the use of a catalyst and description of the feedstock. So the general idea corresponds with the final assignment, but the kind of details are different.

The questions are made in such a way that all the important aspects are dealt with in order to give a complete picture of the content relevant to this capstone. So also questions considering pre-treatment or catalysts are asked for example. In this way it could help them to see what the final assignment will be about.

5.3.2 Giving an advice related development

For the guidance in giving an advice the same example report is used and questions are developed. Also this part should be in the light of the whole skills, according to the 4C/ID model. The same report is used to give a complete picture of this whole skill.

The questions developed differ from the previous developed part in the way feedback is provided. Another form of multiple choice questions is used: peer-instructed multiple choice. In these kind of questions still multiple answers are presented, but the student has to write a motivation for a chosen answer. After submitting this answer and motivation, the motivation of other students is presented. The student can change the originally chosen answer and after submitting this second answer, the systems gives the final feedback.

Using these kind of questions, a student really has to think about a chosen answer. Thereby a student gets insight into how others think and there is a form of interaction among students. As discussed in chapter 4.3, facilitating this interaction is important for successful online education.

5.3.3 Final assignment related development

The final assignment, as made by Harry (appendix A), is slightly adjusted in the capstone (appendix E). To better fit the learning goals of the capstone, students also have to consider biochemical catalysts, instead of only homogenous and heterogeneous catalysts. Furthermore, the focus of the report is explicitly mentioned to clarify to students what the report should be about.

Next to the content of the final assignment, also some guidance in writing the report was preferable. A checklist for the components of a report is made, where short descriptions of these components are presented, as can be seen in appendix E. It is also considered to develop questions to clarify details for writing the report, but it is not clear what guidance is needed by students. When Iris made the final assignment from a student's perspective, only the style of writing was remarked. It is not the focus of the capstone to reach a certain writing style, so instructions about writing style are considered less important. Furthermore, it is hard to predict if students need more guiding in writing, so only the checklist is developed at this stage.

If students have made the report, they will have to give feedback to peers. It is chosen to let students give only feedback and no assessment, as explained in chapter 5.2.3. A short instruction for giving this feedback is made to help students to check reports of peers. This method is useful to help students to see maybe other perspectives or ideas and to help them look critically to their own report afterwards. Students can use the feedback to improve their report and hand in a final version, which will be graded by a teacher as discussed in chapter 5.2.3.

Although some guidance is given to students, with all the information and question developed in order to finally write a report, students still will have questions. These questions can be asked in a discussion forum what should be monitored by a teacher or moderator of the capstone. The discussion forum is chosen because this will work regardless of the number of students. Other ways of answering these questions can be considered, but will be discussed in chapter 6.

6. Perspectives

After developing the capstone project, some interesting perspectives can be given. Below some perspectives and recommendations about the used model and future perspectives are given.

6.1 Development with the four component instructional design model

For the development of this capstone project, the 4C/ID model was chosen. In retrospect it is used less than intended. This model fitted the learning goal of the capstone, but the four components should be used more for a complete design according to the 4C/ID model. The general idea of the 4C/ID model to put everything in perspective of the whole skill and increase complexity among the different tasks is used. When using the 4C/ID model in detail, multiple task classes, containing multiple tasks, should be developed. But since the capstone is not the start for students, but the MOOCs are, a lot is already learnt when starting the capstone. The developed capstone has two modules, which can be considered as separate task classes. Every task class should consist of multiple tasks of the same level of complexity where the amount of guidance is decreased. But the content of the task classes is more like one big task. More tasks could be developed, but seemed unnecessary. Most of the supportive information for the questions and writing the report is given in the MOOCs. Since there is no need for automated or flawless skills, also no part-task practice is developed. Some just-in-time information is developed in order to let students successfully complete the questions. So in general, for development of materials completely according the 4C/ID model, more tasks and task classes should be developed.

6.2 Recommendations

Before the developed capstone is implemented in the online platform Edx, some options could be considered. One idea is to replace some written instruction by a spoken video. This fits better in the design of the MOOCs and gives a nice variation in all written instructions. For example, the goal of the final assignment could be explained by Harry in a video. Another idea could be to include references in the feedback of the multiple choice questions to the corresponding MOOC module, so a student who does not know the answer, knows which knowledge should be refreshed. A last idea is to check the developed capstone. Although it is explored what is possible in the online platform Edx, it is advisable to check whether all the chosen options are feasible in Edx.

Dependent on the number of students that will start in the same period of time with the capstone, some options for communication between students and the teacher could be considered. It is suggested to use a discussion forum to facilitate a way to ask questions for students and use a moderator or teacher to answer these questions. This works for small and for larger groups of students, so this is an easy way to start with. It is expected that at the start of the capstone the group will be about 10 students. In that case it is also possible to schedule several appointments to ask questions by Skype for instance. This could cost less time than answering each question individually in that case. It has to be kept in mind that students could work in different time zones all over the world, but this could already be manageable with two appointments. An alternative could be to gather the questions in advance and answer them in a video, so students can watch the video whenever suits them. Or a combination of both could be made. For the long term, frequently asked questions could be gathered and published in the capstone. This helps students to get their answers easily and safes time for the moderator or teacher.

If the group of students will be small, it could also be considered to let students defend their advice in a short video. Using a video, students have to summarize their report and explain their choices shortly. This gives another way of assessing students, additionally to the written report. If students have to make this video, this needs some additional instruction in the capstone. Not everyone is familiar with making videos, so an instruction should include guidelines for the content of the video and suggestions how students can make this video, such as recording programmes.

If the group of students grows rapidly, the capstone itself still is useful, but some practical issues could arise. Maybe the chosen way of answering questions of students should be adjusted or additional teachers or moderators are necessary to assess all the reports in time.

Independent of the number of students, the capstone should be evaluated after the first group of students finish. Looking at questions they have asked and the reports they have made, it should be possible to see if the capstone has to be adjusted. Also a student survey could be used to check what students liked and what could be improved. It could be interesting to look if additional guidance is necessary in writing the report. So for example if exercises on writing are useful.

7. Conclusion

Since the micromaster should have a capstone project to complete the programme of five MOOCs, the goal was to develop this capstone project. At the end of the capstone, students should be able to design and evaluate a biobased process. This concerns higher-order thinking skills, which should be assessed with this capstone. It seemed this assessment needed special attention, because of the online environment of the capstone. Literature was reviewed, but was found very limiting on this subject. It was thought assessing higher-order thinking skills is more a concern of practical implementation, because in this case the same assessment strategy of writing a report was chosen. So assessment of higher-order thinking skills could be the same for online and on-campus education, but practical implementation could differ.

Furthermore, online education differs at more aspects from on-campus education. For this project two aspects were interesting to take into account in the development of the capstone. One aspect is student interaction with the content, teachers and other students, which is found important for successful education. This applies to both kinds of education, but in the online education of a capstone, people are separated in time and place. This has not to be a problem for on-campus education. Interactions have to be integrated and facilitated in the design of the capstone. It is tried to reach enough of these interactions by using options to get feedback from other students, making questions about the content, facilitating asking questions to a teacher and organising and managing a discussion forum.

A second aspect is the guidance in writing a report that is clearly necessary from experiences in on-campus education in general. From the analysis performed by making the final assignment from a student's perspective it was found that it is hard to know what is expected from the description of the assignment. One module of the capstone consists of questions to guide students through an example report. In this way some guidance is provided. These questions are also meant to refresh knowledge and indicate what the relevant parts of the report should be. Hopefully in this way the guidance of a teacher seen in on-campus education is reduced.

With these aspects and options in mind, the whole capstone project is developed using the explored possibilities in the online platform Edx. The developed capstone consists of two modules. The purpose of the first module is mainly to refresh knowledge and integrate the separate MOOCs and secondly to explore the concept of writing a report about an advice for a biobased process. In the second module students make a report about their own advice, where they have to design and evaluate a biobased process. So with these two modules the overall goal of this project is achieved.

Acknowledgements

It was really nice that I got the opportunity to work on this project. I was searching for a project where I could combine chemistry and education, ‘something different’ I would say. Therefore, I would like to thank Harry Bitter and Sanne Mirck, who came up with the idea for this project. Of course I also would like to thank Harry for his supervision and the helpful conversations we had. For good advice or a new idea on the educational aspects, I could count on the help of Sanne. I would like to thank her for all her feedback.

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Appendix

Appendix A: Final assignment instruction

Case: deoxygenation of vegetable oils

The scene

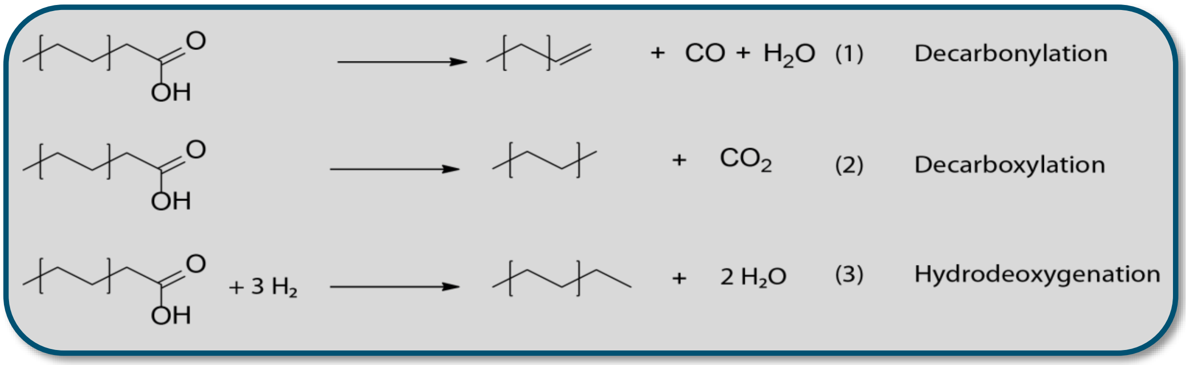
I am an investor and want to invest in state of the art biomass processing plants. Currently I want to invest in a plant which makes diesel-like fuels from vegetable oil-like feedstocks.

Current biodiesel

A biobased alternative for fossil based fuels is a biobased fuel like biodiesel. Biodiesel is an ester from vegetable oils and fats with methanol. These are the so called FAMEs (fatty ester methyl esters). The drawback is that these FAMEs can only be blended to the fuels of our cars and not used pure.

Alternative

An alternative is the deoxygenation of vegetable oils. In that reaction vegetable oils are deoxygenated in one of the following three ways (here the reactions are given for the deoxygenation of fatty acids).



It is this alternative I am interested in.

The relevant reactions can either be performed by homogeneous catalysts [ref: Le notre] or heterogeneous catalysts [ref Murzin for Pd; ref Gosselink for W2C]. Please give me an advise how a plant in which I need to invest should look like. I want to make 10.000 tons/year of renewable alkanes/alkenes.

In your advice please address the following issues (max 10 pages)

- what is the feedstock I should use
  - Keep in mind the sustainability
  - Keep in mind the pretreatments needed
- Choice of catalyst and reactors
- Purification steps needed
- Overall costs (maybe only qualitative)
- Overall sustainability.

Appendix B: Final assignment from student's perspective

A process for the deoxygenation of fatty acids for the production of biodiesel

Most of our energy, especially fuel, is based on fossil sources. In order to make sure that future generations still have enough energy sources and to slow down climate change, more renewable energy sources should be used. In recent years the interest for biodiesel is increased. It is already possible to produce diesel based on biomass. So called fatty acids methyl esters (FAMES) are produced from fatty acid containing biomass to create biodiesel.

The process to make FAMES is relative simple and already feasible. A major drawback of using is FAMES based biodiesel is incapability of replacing petrochemical diesel using current car engines. This is the reason why an alternative biofuel is preferred. FAMES cannot be used as a pure biofuel due to its high oxygen content. In order to use fatty acids as source for producing biodiesel, these oxygen groups should be removed in order to produce n-alkanes and n-alkenes. This process is called deoxygenation. [1]

To be able to produce biodiesel from fatty acids via deoxygenation reactions, a new process should be designed. This includes a suitable feedstock, conversion method and purification steps and taking overall costs, sustainability and feasibility into account. This process should be used in a new built plant, which is capable of producing 10,000 ton biodiesel a year.

Feedstock

For the production of biofuel out of fatty acids, several feedstocks can be considered. The most common feedstock includes virgin vegetable oils, animal fat and waste cooking oil or grease. These feedstocks contain each a certain composition of fatty acids, but are all suitable for biofuel production. In general fatty acids are mostly present in feedstocks as triglycerides. To be able to deoxygenate the fatty acids, these triglycerides need to be hydrolysed. Further steps depend on the feedstock. For each feedstock pre-treatment, costs and sustainability aspects will be considered.

Virgin vegetable oils

Virgin vegetable oils are obtained from crops rich in oil, for example rapeseeds, sunflower and jatropha. [2] After harvesting, these crops have to be pressed and filtered in order to free the oil content. Subsequently the fatty acids have to be separated from the water phase by heating the mixture. Before deoxygenation can take place, phospholipids need to be removed by degumming.

A big disadvantage of using virgin vegetable oils is the need to cultivate crops for fuel production. These crops compete with food supply by the use of arable land. Cultivation also takes a lot of time and has its own costs. Since most crops cannot be cultivated during the entire year, the crops need to be transported and the oil content needs to be stored after harvesting in order to be able to produce fuel the entire year.

Animal fat

Animal fat is obtained in a process called rendering. Animal residues are cooked, which separates fat, bones and other residues. Before animal fat can be processed, several pre-treatment steps have to be considered. Due to contaminations like plastics, polyethylene is formed, which can be removed by filtering. Corresponding to the virgin vegetable oils, phospholipids need to be removed by degumming. Citric acid or phosphoric acid can be used. In rendering a high temperature is used, which leads to the formation of polymers. The overall viscosity will raise and the easiest solution is to mix several batches. Depending on the composition of the animal fat, also sulphur components might be removed. It is regulated in which order fuels may contain sulphur components. Only vacuum distillation is suitable to remove these components. [3]

Because rendering already takes place at multiple places, animal fat has to be transported in order to process it. Animal fat is already used for all kinds of purposes, but using it as biofuel is possible. These categories are made based on the risks of spreading diseases. Only one category might be used for consumer purposes, like cosmetics or pet food. All categories could be used for biofuel production, though the quality of biofuel made for consumer purposes might by higher. [4]

Waste cooking oil

Waste cooking oil and grease can be collected and used as feedstock. Considering it is waste from cooking, first food residues have to be removed, which probably can be done by filtration. Grease can also be collected by trapping in the drain, which means also other contaminants like emulsifier and water need to be removed. [5] Because trapped grease is solid when trapped, it has bad low temperature properties for fuel purposes. It is easier to use liquid waste cooking oil for fuel production.

Since waste cooking oil is already waste, it is easy to get this feedstock. After collecting waste cooking oil, it has to be stored, but it is available all year long. Disadvantage of using waste, is the limiting availability. Waste cooking oil has to be collected from households and catering industry and the supply will not depend on its demand. At the scale of 10,000 ton a year, the use of this feedstock should be feasible. Advantage is the relative easy way of processing. [5]

Conversion

Deoxygenation of fatty acids can be obtained via three different reactions: decarboxylation, decarbonylation and dehydrodeoxygenation. All reactions can be seen in figure 1. Some reactions consider only one type of deoxygenation, where others combine reactions. For a dehydrodeoxygenation reaction addition of H_2 gas is necessary.

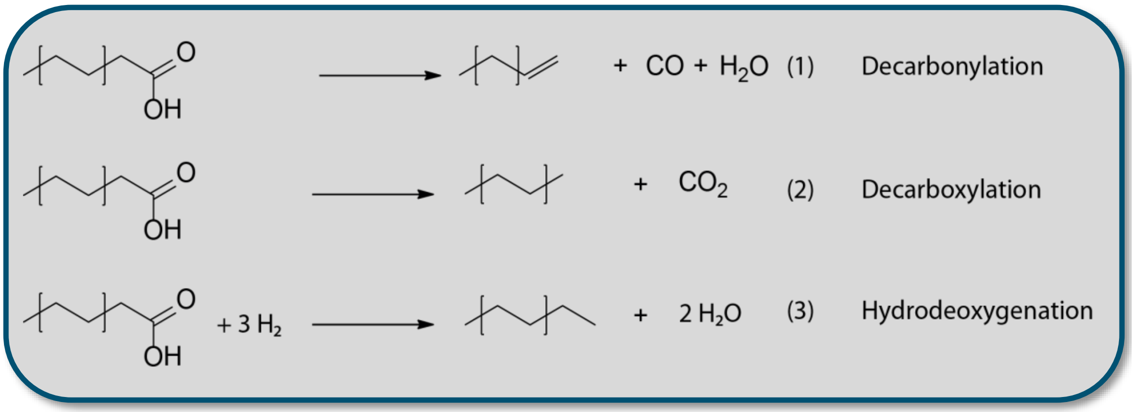


Figure 2: Deoxygenation reactions

For the deoxygenation of one of the feedstocks, two types of catalysts are considered: homogenous and heterogeneous catalysts. In general some differences can be addressed. At one hand heterogeneous catalysts are easier separated from the reaction mixture after conversion and therefore easier recycled if possible. At the other hand is mixing of a homogenous catalyst and a reaction mixture easier obtained. As examples silver(I)salt combined with sodium peroxydisulphate, carbon-supported palladium (Pd/C) and supported tungstencarbide (W_2C) are used.

Silver(I)salt

Silver(I)salt (combined with sodium peroxydisulphate), a homogenous catalyst, is used to decarboxylate fatty acids. The proposed mechanism of this reaction shows subsequent oxidizing and reduction of the silver ion yielding in a radical at the carboxylic acid moiety. After cleavage of CO_2 an alkene or alkane containing a radical is formed. This radical reacts with a solvent-H to alkenes or alkanes. This process is selective to carboxylic acids, but radical formation can be problematic. Since the proposed feedstocks obtain also unsaturated fatty acids, polymerisation cannot be prevented. High polymer content leads to a high viscosity, which will lead to problems downstream and a lower fuel quality. The stability of the catalyst itself is not clear. [1]

Since this catalyst is a homogenous one, an additional step to separate the catalyst from the mixture is necessary. Due to regulations about the sulphur content in fuels, the catalyst should be removed properly. A way to separate this catalyst is by precipitation followed by filtration. In this situation recycling of the catalyst not possible anymore. In general separating and reusing a homogeneous catalyst is hard. The catalyst itself is relatively cheap and does not need any preparation before use.

Carbon-supported palladium

Pd/C is a more common used catalyst in for example hydrogenation of alkenes or deoxygenation reactions. In that sense is Pd/C not selective, but more selectivity for longer alkane chains can be obtained by choosing the right carbon support. Addition of hydrogen gas allows hydrodeoxygenation to perform as well. Pd/C is capable to reach high conversion of several fatty acids. [1, 6]

Since Pd/C is a heterogeneous catalyst, separation from the reaction mixture is easily performed by filtration. In this fashion the catalyst can be recycled. The stability of the catalyst is not clear. Depending on the support, a Pd/C catalyst could be commercially available or has to be prepared in advance. Preparation can raise the costs of the catalyst significantly. The use of hydrogen gas in this reaction also raises the costs. The reaction is performed at 300 °C under 17 bar H_2. [6]

Tungstencarbide

Supported W_2C is another example of a heterogeneous catalyst. It is capable of decarboxylate, decarbonylate and hydrodeoxygenation fatty acids in the presence of hydrogen gas. A carbon nanofiber (CNF) support is used and impregnated with ammonium metatungstage. Depending on the preparation temperature, tungstencarbide and/or tungstenoxides are disposed on the CNF surface. Tungstencarbide shows the highest deoxygenation conversion and is selective for hydrodeoxygenation, which is yielding longer carbon-chains. These longer carbon chains are favourable for the use as fuel. [7, 8]

A disadvantage of this catalyst is the preparation. This catalyst is prepared at a temperature of 1000 ˚C and also CNFs have to be prepared separately using other catalysts and high temperatures. An advantage of this catalyst is the reusability. Tests show no loss in activity for the W_2C catalyst. Considering W_2C is a heterogeneous catalyst, this catalyst can be separated by filtration and easily reused. In this reaction a constant pressure of hydrogen gas is needed. The reaction is performed at 350 °C under 50 bar H_2. [8]

Reactor

Separately from the catalyst a reaction has to be performed in a reactor. Considering a batch reactor and a plugflow fixed bed reactor, the latter one seems more suitable. At a scale of producing 10,000 ton a year multiple batches have to run simultaneously in order to reach that goal. A continuous flow seems more feasible to reach that goal. Also due to the formation of a lot gasses in a deoxygenation process (CO, CO_2, H_2O and/or small alkanes) a huge pressure built up will occur in a batch reactor, which have to be taken into account. It is easier to manage this in a continuous flow.

Purification

In every deoxygenation reaction by-products are formed. Depending on the type of reaction (decarboxylation, decarbonylation and hydrodeoxygenation) this at least means formation of CO, CO_2 and/or H_2O. Since the product is liquid, separation of these gasses is easy and this needs no special purification step. Depending on the feedstock additional by-products can be formed. In all mentioned feedstocks, fatty acids originate mostly from triglycerides. After hydrolysis of triglycerides glycerol is formed and should be removed for a good quality fuel. Since the density of glycerol is relatively high, separation can be done by centrifuging. Other by-products can consist of short chain alkanes. Depending on the overall composition of the mixture, these need to be removed. A high content of short chain alkanes can influence the properties of the fuel. These alkanes can be removed by distillation. [8]

There is also an example of the use of waste cooking oil as feedstock using a ruthenium heterogeneous catalyst for deoxygenation where no pre-treatment and no purification is performed. The physical properties of the obtained biofuel corresponds with the ones from petroleum based diesel. [9] This illustrates that the purification steps needed depend on the feedstock and catalyst choices.

Overall costs

Considering the feedstock options, animal fat is probably cheaper than virgin vegetable oils. In the European Union Germany is by far the largest producer of animal fats. In 2014 all categories of animal fats were cheaper than palm oil (316.5-352.4 vs 399.4 euro/ton) [4] Animal fat is already used in biofuel production and the price is probably high due to this demand. [10] So the price is hard to predict when used more in biofuel production.

Using waste cooking oil as a feedstock is more expensive than virgin vegetable oil in terms of processing, but waste cooking oil itself is cheaper than virgin vegetable oil. [5] In a study comparing different feedstocks for a transesterification process for biofuel on several scales, waste cooking oil looks the cheapest feedstock for overall processing and purchasing costs. This is of course for another type of conversion, but most of the processing steps necessary should be comparable. [7]

Of the earlier mentioned catalysts the silver(I)salt homogenous catalyst is the cheapest one. It has to be noticed that the consulted costs of these catalysts or the starting materials are in small quantities. [11] Besides the purchase of a catalyst, the two mentioned heterogeneous catalyst need (multiple) preparation steps, where the homogenous one can be used directly after purchase. The big difference is the opportunity of reusing the catalyst. The costs of reusing one of the heterogeneous catalysts will be lower than reusing a homogenous catalyst. Since reusing the catalyst is lucrative at a scale of 10,000 ton a year, these low costs weigh up against the cost of purchasing and preparing a catalyst. In that sense is a heterogeneous catalyst more cost-effective.

Conclusion

Taking all the mentioned options into account, choices about a process to make biodiesel from a fatty acid feedstock can be made. Taking sustainability and overall costs in to consideration, used cooking oil seems the best option as feedstock from the options described earlier. It is relative cheap to obtain and available throughout the year. Since it is already waste, it is favourable to use it as feedstock from a sustainable point of view.

This feedstock have to be converted using a catalyst. Heterogenous and homogeneous catalysts are considered and at this point, using W_2C seems most promising. This heterogeneous catalyst has advantages of easy separation by filtration and proven stability in reusing. At a given scale of 10,000 ton a year reusing a catalyst is also a favourable way to go from a sustainable point of view. Proven selectivity for longer chain alkanes yields in better biofuel quality. This ways up against relative higher purchase costs of the starting materials and preparation for this catalyst. In the reaction using W_2C a constant pressure of H_2 gas is used. In general, to form longer alkane chains H_2 gas has to be used. From a sustainable point of view this is not favourable, but it is necessary for a high quality fuel. It has to be said that also other heterogeneous catalyst could be considered, but from this selection, it seems the best option. It is tested on laboratory scale, so checking performance it larger scales is recommended.

Considering two types of reactors (batch reactor and fixed bed plugflow reactor), a fixed bed plugflow reactor should be used. Due to the scale and formation of gaseous by-products this type of reactor seems more suitable to manage to process.

After conversion of the used cooking oil, the catalyst can be reused after filtration and the formed fuel needs to be separated from the glycerol. Using centrifuging techniques a biofuel should be obtained. Depending on the final composition, properties of this biofuel need to be compared to petrochemical based diesel in order to see if distillation is necessary. Distillation can separate short chain alkanes and alkenes from longer ones in order to improve fuel quality.

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Appendix C: Assignment possibilities on Edx

The online platform Edx has several options to make assignments. These possibilities are explained in a short course produced by Edx to give insight in all possible questions that can be asked to a student.

The possibilities are:

- Multiple choice questions
    - One answer possible
        - Optional use of peer-instruction: A student choses one answer and types an explanation for its answer. Next this student can see what others do and why they chose a certain answer. The student gets a second chance before the system gives feedback.
    - Checklist: several answers possible
    - Dropdown: select an answer in a field from a list of options
- Open response (combinations of options below possible)
    - Student training: after completing a response, students can check their own work using a provided rubric in order to improve the given response.
    - Self-assessment: after completing a response, student check their own work using a provided rubric and give a score.
    - Peer assessment: after completing a response, students check each other’s work using a provided rubric and give a score.
    - Staff-assessment: after completing a response, staff check the work and give a score.
- Fill-in: short answer or number which can be filled in in a box.
- Drag-and-drop: placing (text) items in a figure. Useful for making connections or making sequences.
- STEM (science, technology, engineering, mathematics) problems: a fill in box for making equations, using special characters (such as Greek or units), doing calculations or checking code.

All these options, except open ended questions, can give feedback to the students after choosing an answer. For open ended questions a rubric can be used or feedback from a teacher. For all these options, except open ended questions, also an optional hint can be added.

Appendix D: Capstone material – content and advice related

Reading instruction:

- This content is written as suggested texts for the online platform Edx.
- Italic presented content is meant to give information about practical implementation. These parts should be removed for the final capstone.
- Underlined numbered headings are a suggestion for the chapters and sections of the capstone and meant to see to overall structure.
- Bold depicted texts are meant as headings for the text.

In this suggested material, an adapted report of other students has been processed and used as example. This report was obtained through Maurice Franssen and was written by students Walter de Koster, Oriol Cabau, Zhen Chen, Sabine van Oossanen and Daniël Emmery.

Module 0: Overview

General description of the capstone and all the details which are also mentioned in other MOOCs in 'module 0'.

Explaining that the capstone will consist of two parts: module 1 (this appendix) focusses on preparation for the final assignment by reading and doing quizzes. In module 2 (Appendix E) *the final assignment is made and this part will be graded.*

Outline Module 1

1.1 Welcome
1.1.1 Overview
1.1.2 Advice

1.2 Understanding an advice
1.2.1 Mandelic acid (and the adapted student report)
1.2.2 Assignments 1
1.2.3 Assignments 2

For readability the adapted student report, which should be after the introduction of mandelic acid, is placed at the end of this appendix.

Module 1: Preparation

1.1 Welcome

1.1.1 Overview

For most compounds of commercial interest there is not just one way of producing. Companies have to consider several possibilities and carefully weigh all advantages and disadvantages before they choose for one specific production method. There are no strict rules which one can follow during this process. Not only the process and chemical costs are involved, but also environmental aspects and specific consumer demands play a role.

You have learned about all the different steps in a biobased process and the aspects you should consider before choosing for a certain process. The next step is to make an advice on which method should be used for a desired product.

1.1.2 Advice

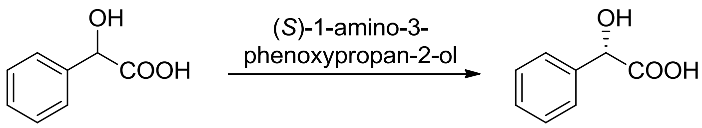
If you want to be able to give an advice about how to produce a desired product by a biobased process, first you should find relevant methods to get the desired product(s). To help you to get more insight in the information you need, we are going to look at an example about mandelic acid. This report is made by students at the Wageningen University as part of a course. This assignment was similar to the assignment you will make at the end of the capstone. After you read the report about mandelic acid, you get some questions to help you think about this advice.

1.2 Understanding an advice

1.2.1 Mandelic acid

Mandelic acid is a simple chiral acid that is used in medicine and as a precursor for chiral drugs. For use in medicine and drug development, mandelic acid has to be enantiomeric pure. There are many ways to prepare it in enantiomerically pure form. Two of these methods are given below.

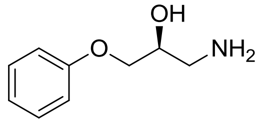
A



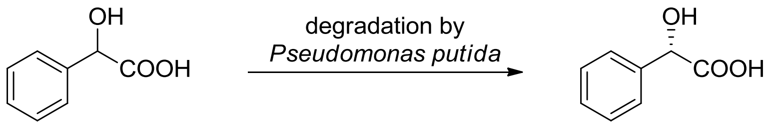
mandelic acid
(racemic)

L-mandelic acid

(*S*)-1-amino-3-phenoxypropan-2-ol =



B



mandelic acid
(racemic)

L-mandelic acid

As can be seen, method A uses a chemical route and method B uses a microorganism to get the enantiomerically pure form of mandelic acid. These two methods will be explored and compared to see which methods fits best for the production of enantiomerically pure mandelic acid at an industrial scale.

After this introduction the adapted student report should be presented here (maybe in multiple sections), but for readability this report can be found at the end of this appendix.

1.2.2 Assignments 1

MC question:

- In both methods solvent extraction is used. This step is used for:
  - Conversion
  - **Separation**
  - Recycling
  - Pre-treatment
    - Using solvent extraction, the product is separated from all the other components in the mixture. So the product is separated from the mixture.

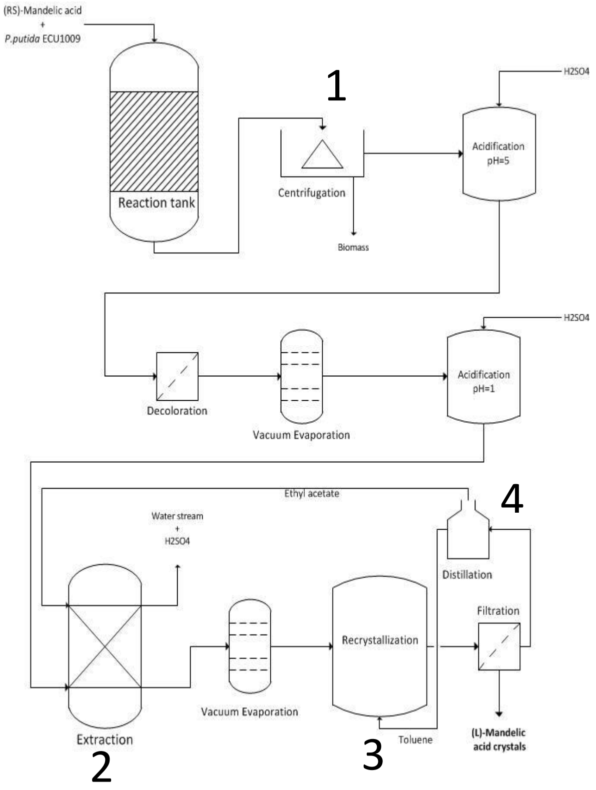
MC question

- In method B recrystallization is used. What is the purpose of this step?
  - More product will be obtained

- **A higher purity of the product will be reached**
- In order to obtain a solid product
- To separate the solvent from the product
  - Recrystallization is a purification step. Due to recrystallization impurities will be solved in the solvent and the product will precipitate eventually.

Drag-and-drop question

- In the figure you see method B schematically. Place the right labels by the indicated process steps.
  - Label options: separation 2x, purification, recycling 2x, pre-treatment, conversion



1 = Separation, 2 = separation, 3 = purification, 4 = recycling

MC checklist question

- In this case, the feedstock is not mentioned. But which aspects are important to consider when choosing a pre-treatment for a feedstock in these two methods?
  - **Where mandelic acid is located in your feedstock**
  - **If your feedstock is pure after the chosen pre-treatment**
  - **The yield of mandelic acid after pre-treatment**

- **That you make sure you end up with solid or water solved mandelic acid**
  - If you know where mandelic acid is located, you know which barriers you have to overcome and what kind of pre-treatment is necessary.
  - In method B a microorganism is used, so it is important to know if other components are present and if this microorganism still functions with these components.
    It does not necessarily have to be an problem if other components are present in case of method A, but if so, you have to make sure you separate these components from your product in this downstream process.
  - If you want to choose a pre-treatment, you of course have to know if that pre-treatment gets all possible mandelic acid out of your feedstock.
  - In both methods mandelic acid is added as solid and water is added for conversion.

MC question

- Is the use of a resolving agent (*(S)*-1-Amino-3-phenoxypropan-2-ol in this case) catalytic?
  - Yes, because it is used to convert the mandelic acid
  - Yes, because it can be recycled
  - No, because you need stoichiometric amounts
  - **No, because it does not enhances the reaction rate**
    - A catalyst is used to enhance the reaction rate, but in this case the resolving agent is part of the reaction. There is no reaction to perform without the resolving agent.

MC question

- In method B the organism *P. Putida* is used in order to obtain only (S)-mandelic acid. Is this reaction selective?
  - **Yes**
  - No
    - The organism gets the racemic mixture and consumes only one *(R)*-mandelic acid.

MC question

- In method B: "...*the reaction is carried out in a fed-batch reactor to avoid substrate inhibition at high mandelic acid concentrations."*
  Another reactor type for this method could be a batch reactor. Which statement is true in this case?
  - In a fed-batch reactor batches of product can be removed, where the product stays in a batch reactor till the reaction is stopped.

- **In a fed-batch reactor a higher concentration of desired product can be obtained than in a batch reactor.**
  - In a fed-batch reactor, one batch can be fed with starting material over time. Due to inhibition of *P. Putida* by a mandelic acid concentration of 2%, mandelic acid is added in batches. Since *P. Putida* consumes half of the starting material, the concentration is lower when the second batch is added. In total more starting material can be added before inhibition starts in contrast to adding the starting material all at once.

MC checklist question

- In case of a batch reactor:
  - There is a steady concentration of starting material throughout the whole process
  - **Starting material is added all at once**
  - **Reaction products can only be obtained after the reaction is completed and stopped**
  - There is a continuous flow of reaction mixture
    - In a batch reactor, everything is added at once and after the reaction is stopped, the mixture is taken out of the reactor.

1.2.3 Assignments 2

You have all the essential information about all the important aspects. You know what possible methods are. Now it is time to look at the advice. You have to compare the different methods and consider which method fits the given situation best.

Consider an industrial scale of 10,000 ton a year.

The questions below consider peer-instructed questions. You have to choose one option and give your motivation for that answer. After submitting this answer, you can read motivations of others. You may submit an answer a second time.

MC question with peer-instruction

- In terms of costs, considering only chemicals, which method do you advice?
  - **Method A, because it is less expensive**
  - Method B, because it is less expensive
  - Costs will be about even
    - Method A has a higher profit margin considering re-use of the resolving agent, solvent and base and the added value of calciumsulphate. A first investment is higher for method A, but considering industrial scale, this will be a good long-term investment.

MC question with peer-instruction

- If you take process costs, like energy use, into consideration, which method do you advice?
    - **Method A, because the process costs will be lower**
    - Method B, because the process costs will be lower
    - Cannot be said.
        - The energy costs for method B will be higher due to the overall heating time of 48-120 hours with respect to 11 hours of method A. Besides heating, also evaporation, recrystallization and distillation consumes more energy with respect to steps in method A.

MC question with peer-instruction

- If this process would be used on an industrial scale of 10.000 ton a year for bulk chemical production, which method would you advice in terms of valued products?
    - **Method A gives more valued products**
    - Method B gives more valued products
    - Both methods give the same valued products, since yield is about even.
        - In method A there is a side product of R-mandelic acid which could be racemized to be used again as feedstock. Or it could be used in another process. In method B this enantiomer is consumed by the organism and therefore lost as value. So potentially there is more value in the output of method A.
          In method B a higher purity can be reached, which is less of importance for bulk chemical production.

Adapted student report

Method A: L-Mandelic acid production by diasteriomeric resolution

The chemical basis of diastereomeric resolution

The two enantiomers in the racemic mixture of mandelic acid have the same physical properties, thus making it impossible to set up a separation process without further chemical operations. Diasteriomeric resolution provides a means of separating the enantiomers by creating a diastereomeric compound. These do have distinct physical properties and this can form the basis of a separation process. In this case it relies on the exchange of a hydrogen atom between the carboxyl-group of mandelic acid (pKa ≈ 5) and the primary amine in the so called resolving agent (pKa ≈ 9). (Figure 3) In the case of mandelic acid, *(S)*-1-Amino-3-phenoxypropan-2-ol is used to create the extra stereocenter. The process of selecting the resolving amine, however, is usually a matter of trial and error. During the exchange of hydrogen between the enantiomers and the resolving agent, an ionic bond is formed between the two.

The two resulting diastereomers have different crystallization points and can therefore be separated. Furthermore, lithium hydroxide has been shown to enhance the efficiency of the resolving agent by competing for it with the enantiomers [1]. In the best case it should compete for the enantiomer that is not the target of the separation process, allowing more of the resolving agent to react with the enantiomer of interest. The resolving agent and mandelic acid can then be separated using a strong acid to protonate the carboxyl group of mandelic acid. The resolving agent will retain its positive charge and this creates an opportunity for solvent extraction. The uncharged mandelic acid will partition to the organic phase, whereas the charged resolving agent partitions to the water phase.

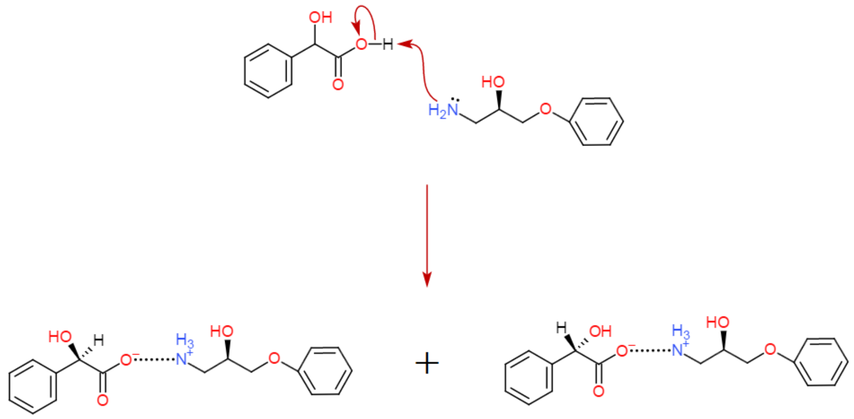


Figure 3 The reaction mechanism of the reaction between racemic mandelic acid and the resolving agent.

Industrial scale process

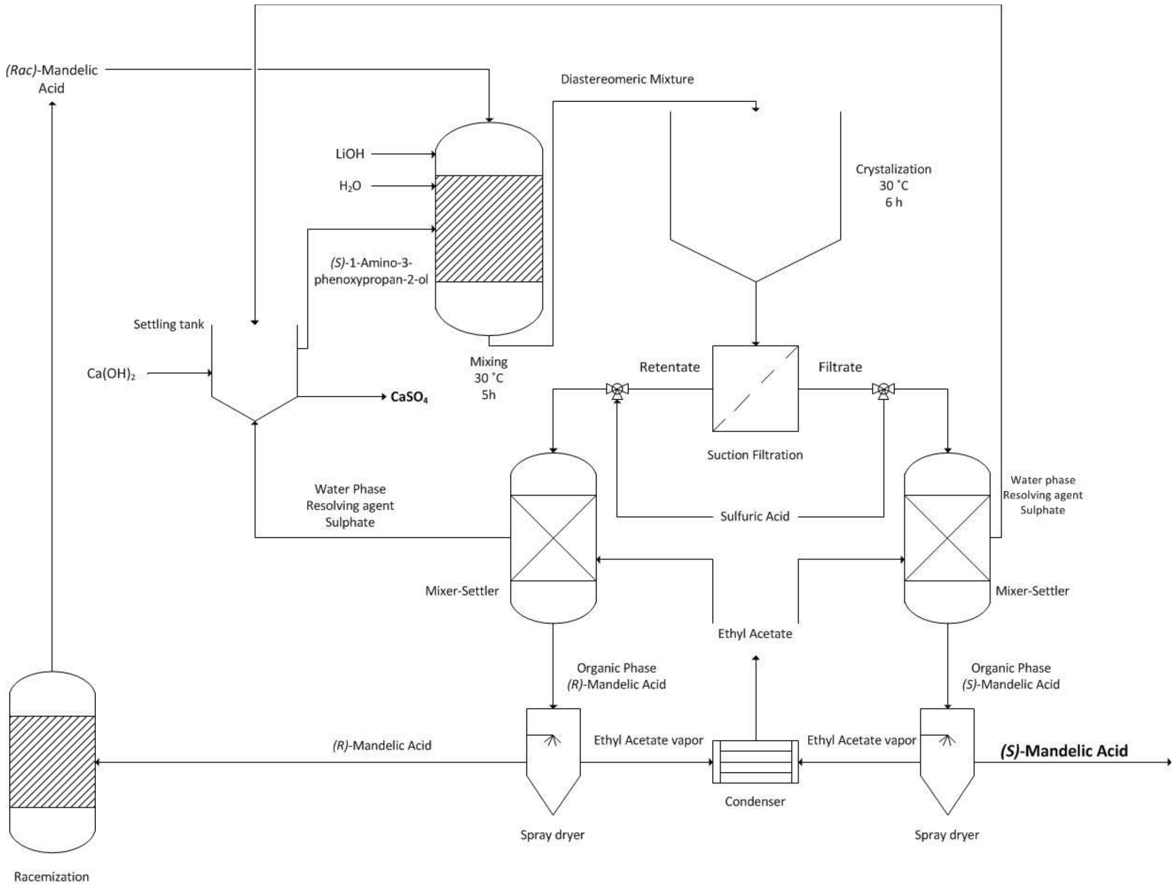


Figure 4 Process scheme of the chemical purification of L-Mandelic Acid from its racemic mixture using diastereomeric resolution.

The mixture is stirred at 30 degrees C for 5 hours, before being crystallized. Next, suction filtration separates the precipitate (L-mandelic acid and the resolving agent) from the filtrate (R-mandelic acid and the resolving agent). Subsequent acidification with sulfuric acid and solvent extraction are used to separate the enantiomers from water and resolving agent [2].

Sulphate left over from the addition of sulfuric acid is prone to accumulation and will have to be removed if the water stream containing the resolving agent is to be recycled. Furthermore, the pH has to be readjusted to deprotonate the resolving agent to allow reuse. These two operations can be combined in the addition of calcium hydroxide. This forms the insoluble calcium sulphate, while the free hydroxide neutralizes the added protons from the sulfuric acid. Moreover, calcium sulphate is more valuable than calcium hydroxide, therefore providing the factory with an extra source of income. The ethyl acetate used in the solvent extraction can also be recycled after removal of mandelic acid by spray drying. Lithium can be added as needed when it is lost through the organic solvent. The purity after crystallization is 85% [1] with a yield of around 49% of the starting mixture.

Safety aspects

The biggest hazards associated with the process are those of the acid and base that are used. The industry is familiar with the handling of these compounds, as well as that of the organic solvent and this should therefore be no objection to the use of these. However, care should be taken that neither lithium ions, nor the organic solvent end up in the environment.

Cost Estimation

The total cost of the one-time chemical purification of *(rac)*-Mandleic acid is as follows:

Table 1 Total cost of the chemical purification of L-Mandelic acid from its racemic mixture using diastereomeric resolution.

Chemicals	Price for eu/mol	Required amount (mol)	Price (eu)
Racemic-mandelic acid	2.33	1	2.33
Sulfuric acid	0.25	0.50	0.13
(S)-1-amino-3-phenoypropan-2-ol	3645.6	0.9	3281.04
LiOH	0.88	0.1	0.09
Ethyl acetate	8.1 (eu/L)	2.54 (L)	20.58
$Ca(OH)_2$	0.383	0.50	0.19
Total Cost		**1**	**3304.36**
(S)-Mandelic acid (e.e. >98.5%)	36.67	.49	-17.97
$CaSO_4$	0.628	0.4984	-0.31
Total Revenue		1	**18.28**
Total Profit		**1**	**-3286.08**

Figure 4 shows that the resolving agent can be re-used, as well as ethyl acetate and lithium hydroxide. Therefore, the costs of these compounds are ideally a one-time investment. In practice, this will not be completely the case but for the sake of simplicity, the daily operation cost is also shown in Figure 4. It must be noted that the final product is not of 98.5% purity and we expect the actual revenue to be lower.

Table 2 Theoretical daily cost of the chemical purification of L-Mandelic acid from its racemic mixture using diastereomeric resolution, excluding 'one-time investments'.

Chemicals	Price for eu/mol	Required amount (mol)	Price (eu)
Racemic-mandelic acid	2.33	1	2.33
Sulfuric acid	0.25	0.50	0.13
$Ca(OH)_2$	0.383	0.50	0.19
Total Cost		**1**	**2.65**
(S)-Mandelic acid (e.e. >98.5%)	36.67	1	-17.97
$CaSO_4$	0.628	0.4984	-0.31

Total Revenue	1	**18.28**
Total Profit	**1**	**15.63**
Profit Margin (%)		**689%**

We can conclude that the cost of this process depends highly on the ability of the producer to recycle chemicals. For example, the resolving agent will have to be reused at least 210 times in order for the process to be profitable.

Racemization of R-mandelic acid

The diastereomeric resolution of any compound has a theoretical yield limit of the abundance of one of the enantiomers, in this case around 50%. Hence the racemization of the unwanted enantiomer could boost yield by allowing it to be recirculated into the resolution process. For mandelic acid and other secondary alcohols, serval racemization technologies have been developed: irradiation [3], catalysis using a ruthenium complex [4] and biocatalysis using an enzyme (W110A) from *Thermoaerobacter ethanolicus* [5]. Depending on the cost of operation versus the extra income from racemization, either of these might be used for racemization. However, it must be noted that irradiation causes a lot of by-product formation and degradation of mandelic acid and the ruthenium compound is expected to be expensive and to pose a health risk. Hence the use of an immobilized form of W110A is recommended to further increase yield and decrease operating cost.

References:

[1] Wang, P., Zhang, E., Niu, J., Ren, Q., Zhao, P., & Liu, H. (2012). An excellent new resolving agent for the diastereomeric resolution of rac-mandelic acid. Tetrahedron: Asymmetry, 23(14), 1046-1051. doi:10.1016/j.tetasy.2012.06.023

[2] Method for preparing single configuration mandelic acid or mandelic acid derivative by using chiral resolving agent. 2013, CN 102126944 B.

[3] Feng, P. Y., & Tobey, S. W. (1959). Radiation Induced Racemization of l-Mandelic Acid in Aqueous Solution. The Journal of Physical Chemistry, 63(5), 759-760. doi:10.1021/j150575a038

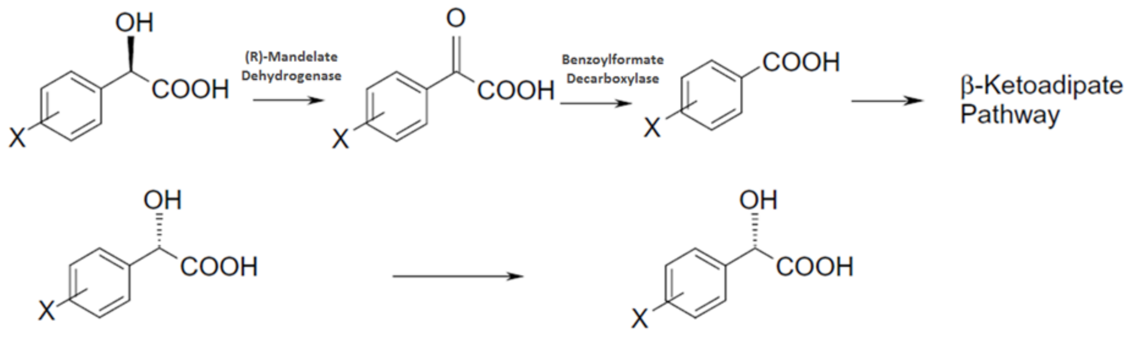
[4] Martín-Matute, B., Edin, M., Bogár, K., Kaynak, F. B., & Bäckvall, J. E. (2005). Combined ruthenium (II) and lipase catalysis for efficient dynamic kinetic resolution of secondary alcohols. Insight into the racemization mechanism. Journal of the American Chemical Society, 127(24), 8817-8825.

[5] Musa, M. M., Phillips, R. S., Laivenieks, M., Vieille, C., Takahashi, M., & Hamdan, S. M. (2013). Racemization of enantiopure secondary alcohols by Thermoanaerobacter ethanolicus secondary alcohol dehydrogenase. Organic & Biomolecular Chemistry Org. Biomol. Chem., 11(17), 2911. doi:10.1039/c3ob27415b

Method B: specific degradation of (R)-mandelic by Pseudomonas putida.

Classification and safety

Method B makes use of the degrading ability of *Pseudomonas putida*. Here, the enzyme *(R)*-mandelate dehydrogenase breaks down specifically the *(R)*-mandelic acid to phenylglyoxylate, so only the *(S)* form remains in the reactor broth [6,7,8]. Using additional native enzymes, the bacteria entirely breaks down the phenylglyoxylate to biomass and CO_2 without producing any additional by products. This method can be described as enzymatic separation of racemates by kinetic resolution [9].



(±)-**1** X=H

Figure 5 The reaction mechanism of the specific degradation of Mandelic acid by Pseudonomas putida.

The maximum theoretical yield that can be achieved for this process is 50% of the starting substrate. This is due to that all *(R)*-mandelic acid is converted to biomass and CO_2. In literature this has been researched and yields of 40-50% have been achieved [3,4,5].

In literature this method has been described and strains of *P. putida* have been isolated, the strains are called NUST506 and ECU1009 [3,10]. Both have in common that they possess a highly specific *(R)*-mandelate dehydrogenase. *P. putida* has the GRAS (generally recognized as safe) status, the only tested difference of these strains to other strains is their ability to degrade *(R)*-mandelic acid while not degrading *(S)*-mandelic acid, to ensure whether these specific strains are safe as well, tests can be performed.

The reagents needed to extract the purified *(S)*-mandelic acid are toluene, sulfuric acid and ethyl acetate. Of these, sulfuric acid is the most hazardous solvent but well known in the industry; care has to be taken to prevent inhalation or skin/eye contact.

Industrial scale process

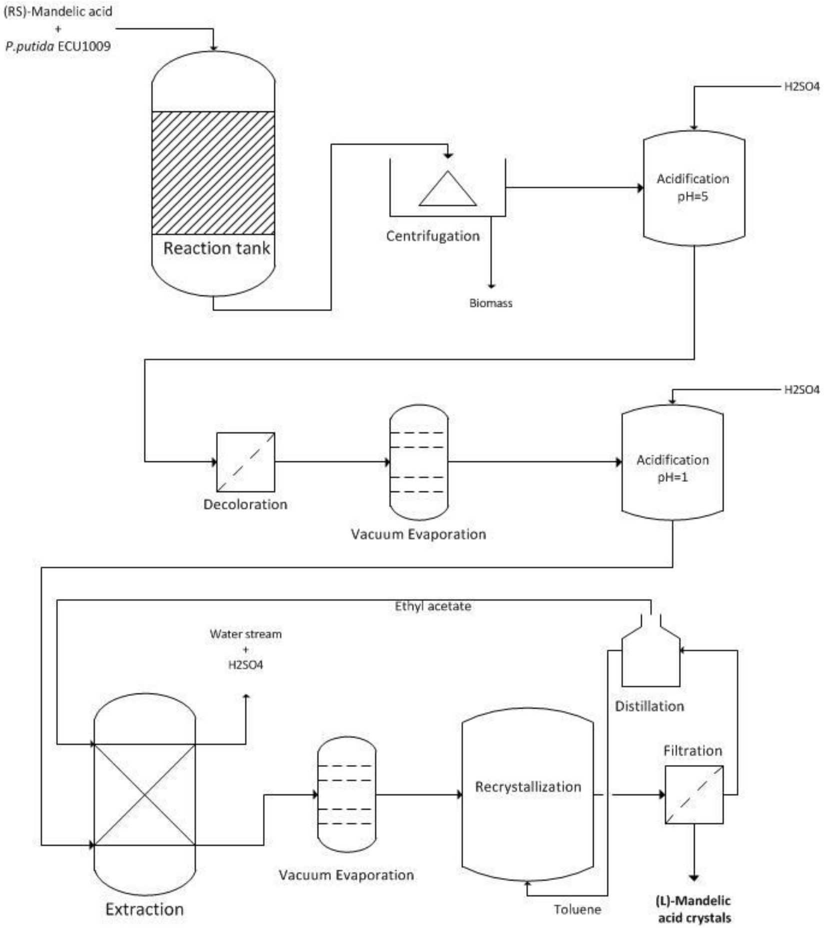


Figure 6 Process scheme of the biological purification of L-Mandelic Acid from its racemic mixture using Pseudonomas putida.

P. putida can be cultivated at 30C at pH 6.5. This pH has been found as the optimum for the highest enantiomeric purity. However, the pH only has a small influence on this purity. The culture time depends on the reactor type and feed concentration, but will be between 48-120 hours.

To start with, the reaction is carried out in a fed-batch reactor to avoid substrate inhibition at high mandelic acid concentrations, which slows down the growth of the bacteria and will lower the end purity of the mandelic acid. Above a mandelic acid concentration of 2%, inhibition will kick in. The ideal quantity of mandelic acid is 1% of *(rac)*-mandelic acid, which is why a fed-batch reactor with an initial *(rac)*-mandelic acid concentration of 1% will be used. The total added concentration of substrate at the end of the fed batch run is 3%.
When the concentration of mandelic acid is very high it is possible to have precipitation of mandelate so before starting the production the critical conditions causing precipitation must be known in order to avoid this phenomenon.

Once the reaction ends the biomass needs to be separated from the water stream, where the *(S)* mandelic acid is. To do that, a centrifugation step will be used and the biomass will be recirculated to the reactor for the next batch. After that, the stream will be acidified with H_2SO_4 to a pH of 5 and then decolorized with activated carbon in order to standardize a correct white color. In this stage of the downstream process should be interesting to reduce the volume of the water stream, just to reduce the amount of compounds needed. So an evaporator working under reduced pressure will be installed and used with this aim. Following the concentration step more H_2SO_4 will be added to lower the pH until 1.

The next step in the process is an extraction with ethyl acetate. Since we are working at a very low pH (below the pKa of the mandelic acid, which is 3.4) almost all our *(S)*-mandelate will end in the ethyl acetate stream that will be concentrated under reduced pressure in order to crystallize the mandelate. The water stream with H_2SO_4 in it should be neutralized adding an alkaline compound. After the concentration step, and due to the crystals produced are not pure enough, a recrystallization unit with toluene will be enough to produce a high quality crystals of *(S)*-mandelic acid which will be separated with a filter. The filtrate, a mixture of toluene and ethyl acetate, will be distillated to separate both compounds with the aim to be able to recirculate them later.

One of the important waste streams is the acidic water stream due to the sulphuric acid. This can be recycled with calcium hydroxide to form calcium sulphate as mentioned in method A.

To end with, a higher quality crystals of *(S)*-mandelic acid will be produced (99.9% at least) with a final yield between 40 and 45%. Taking into consideration that the maximum yield possible is 50% this is a real good yield for the process [3,8].

Cost Estimation

To make a profit of purifying the racemic the value of pure *(S)*-mandelic acid should be a high enough to compensate all the costs. In table 1 a summary of the medium components can be found, including the value of these compounds [8]. The costs of these medium components are expressed as euro per liter reactor medium. This total cost can be compared to the value of the purified *(S)*-mandelic acid.

Table 3 Cost estimation of producing (S)-mandelic acid.

Chemicals	Value (€/Kg)	Concentration (g/L)	Costs (€/L)
(rac)-Mandelic acid	15.34	30	0.46
Corn steeped liquor	9.64	1	0.00964
NH_4NO_3	9.92	1	0.00992
NaCl	3.212	1	0.00321
$MgSO_4$	15.75	0.5	0.00788
KH_2PO_4	8.27	9	0.0744
Total Costs	**-**	**-**	**0.565**
(S)-Mandelic acid (e.e. >98.5%)	241	12-15	-2.89
Total Revenue	-	-	**2.89**
Total Profit	-	-	**2.33**
Profit Margin			**512%**

One cost factor that is not yet taken into account is the cost for electricity. The separation of the *(S)*-mandelic acid requires several steps including a evaporation step to crystalize the mandelic acid. This is an energy intensive step and thus probably a costly step. However, the pure *(S)*-mandelic acid is worth much more than the *(rac)*-mandelic acid. This won't influence the conclusions that can be made about this cost-profit analysis.

The solvent (ethyl acetate) required to extract the mandelic acid from the fermentation broth can be recycled after the crystallization and if the recycling has a sufficient yield than the use of a solvent will not result in high costs.

From the previous information can be concluded that the separation of *(rac)*-Mandelic acid is a profitable process as the end product *(S)*-mandelic acid has a much higher value than the starting substrate. However, this is only true if a high purity of *(S)*-mandelic acid is achieved (e.e >98.5 %).

References:

[3] Feng, P. Y., & Tobey, S. W. (1959). Radiation Induced Racemization of l-Mandelic Acid in Aqueous Solution. The Journal of Physical Chemistry, 63(5), 759-760. doi:10.1021/j150575a038

[4] Martín-Matute, B., Edin, M., Bogár, K., Kaynak, F. B., & Bäckvall, J. E. (2005). Combined ruthenium (II) and lipase catalysis for efficient dynamic kinetic resolution of secondary alcohols. Insight into the racemization mechanism. Journal of the American Chemical Society, 127(24), 8817-8825.

[5] Musa, M. M., Phillips, R. S., Laivenieks, M., Vieille, C., Takahashi, M., & Hamdan, S. M. (2013). Racemization of enantiopure secondary alcohols by Thermoanaerobacter ethanolicus secondary alcohol dehydrogenase. Organic & Biomolecular Chemistry Org. Biomol. Chem., 11(17), 2911. doi:10.1039/c3ob27415b

[6] Wang, J., Feng, J., Li, W., Yang, C., Chen, X., Bao, B., ... & Shi, R. (2015). Characterization of a novel (R)-mandelate dehydrogenase from Pseudomonas putida NUST506. Journal of Molecular Catalysis B: Enzymatic, 120, 23-27.

[7] Kim, B. Y., Hwang, K. C., Song, H. S., Chung, N., & Bang, W. G. (2000). Optical resolution of RS-(±)-mandelic acid by Pseudomonas sp. Biotechnology letters, 22(23), 1871-1875.

[8] Huang, H. R., Xu, J. H., Xu, Y., Pan, J., & Liu, X. (2005). Preparation of (S)-mandelic acids by enantioselective degradation of racemates with a new isolate Pseudomonas putida ECU1009. Tetrahedron: Asymmetry, 16(12), 2113-2117.

[9] Syllabus Applied Biocatalysis, ORC-30306, Wageningen UR

[10] Huang, H. R., & Xu, J. H. (2006). Preparation of (S)-mandelic acid from racemate using growing cells of Pseudomonas putida ECU1009 with (R)-mandelate degradation activity. Biochemical engineering journal, 30(1), 11-15.

Conclusion

After having analyzed both processes independently and taking into consideration all the related parameters such as product purity and process yield, it is possible to make a comparison between the two different processes.

It is important to note that both processes produce sufficient amounts of (L)-mandelic acid to be profitable. However, they do show different advantages to take into consideration. Firstly, the chemical process (method A) presents a shorter turnover time, just 6 hours instead of >50 hours for the biological one (method B). Theoretically, the yield of both processes cannot be higher than 50%. However, the chemical based process would be able to achieve a higher yield by racemization of the recovered (R)-mandelic acid from the previous batch, whereas P. putida degrades the (R) formisomer. This racemization would further boost the (already higher) profit margin of the chemical process, depending on the racemization technique used. In terms of purity, the biological process has higher performance than the chemical one. It is able to achieve a final enantiomeric excess (e.e.) of 99.9% while with method A the resulting product has a purity of 85%.

Nowadays, it is increasingly important to design a sustainable process. A safety analysis was therefore carried out. Recycling of chemicals in method A means that fewer chemicals need to be purchased. As mentioned earlier, the producer should take care that lithium is not released into the environment. Method B can be classified as slightly more sustainable due to the use of a sustainable feedstock and fewer toxic chemicals. Energy costs of method B will generally be higher.

In conclusion, the choice for either one of the methods depends on the criteria that have to be met. Method B is preferred for pharmaceutical applications where a high purity is required, but it has a lower yield and a longer production time in comparison to the other process. Method A is the best option when purity is less important. The process is easy to scale up and is more suited for lower quality bulk production and has the highest profit margin.

Appendix E: Capstone material – final assignment related

Reading instruction:

- This content is written as suggested texts for the online platform Edx.
- Italic presented content is meant to give information about practical implementation. These parts should be removed for the final capstone.
- Underlined numbered headings are a suggestion for the chapters and sections of the capstone and meant to see to overall structure.
- Bold depicted texts are meant as headings for the text.

Outline Module 2

2.1 The assignment
2.1.1 Overview
2.1.2 The case
2.1.3 Checklist writing

2.2 Draft report
2.2.1 Instructions
2.2.2 Writing draft report

2.3 Final report
2.3.1 Using feedback
2.3.2 Writing final report

2.4 Wrap up

2 <u>Module 2: Final assignment</u>

2.1 <u>The assignment</u>
2.1.1 <u>Overview</u>

Now it is up to you! You are going to write your own advice on a biobased process. First you will get the details and instructions of the assignment. With this information, you will make a report about the methods you found and give your advice. Secondly, you will give feedback to reports of your peers. You also receive feedback from you peers, so you can improve your report. Finally, this improved report will be graded by a teacher.

If you have general questions, you can ask them in the discussion forum about this assignment.

A link to a discussion forum about this assignment should be placed here.

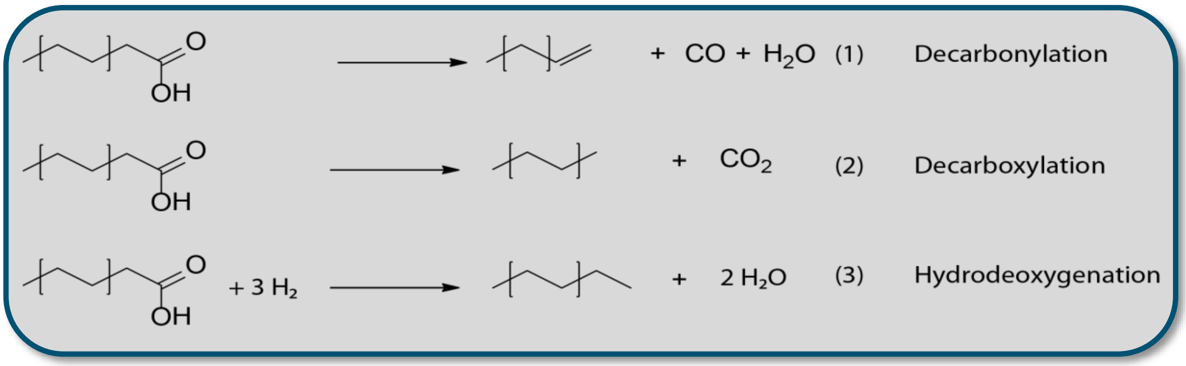
2.1.2 The case

You are going to give an advice about how to perform a deoxygenation reaction. Below you find the case.

The scene
I am an investor and want to invest in state of the art biomass processing plants. Currently I want to invest in a plant which makes diesel-like fuels from vegetable oil-like feedstocks.

Current biodiesel
A biobased alternative for fossil based fuels is a biobased fuel like biodiesel. Biodiesel is an ester from vegetable oils and fats with methanol. These are the so called FAMEs (fatty ester methyl esters). The drawback is that these FAMEs can only be blended to the fuels of our cars and not used pure.

Alternative
An alternative is the deoxygenation of vegetable oils. In that reaction vegetable oils are deoxygenated in one of the following three ways (here the reactions are given for the deoxygenation of fatty acids).



It is this alternative I am interested in.

The relevant reactions can either be performed by homogeneous catalysts [ref: Le notre], heterogeneous catalysts [ref Murzin for Pd; ref Gosselink for W_2C] or a biochemical catalyst.

Please give me an advise how a plant, in which I need to invest, should look like. I want to make 10.000 tons/year of renewable alkanes/alkenes.

In your advice please address the following issues (max 10 pages)

- what is the feedstock I should use
    - Keep in mind the sustainability
    - Keep in mind the pre-treatments needed
- Choice of catalyst and reactors (This should be the focus of your report)
- Purification steps needed
- Overall costs (maybe only qualitative)
- Overall sustainability

Note that the referenced articles are not freely accessible. Maybe a pre-published version of some of these publications could be used. Some literature to start is preferable.

2.1.3 Checklist writing

When writing your report, please use the components below.

- Introduction: Give a general description of the reaction considered. Why is this reaction interesting? What is or are the desired product(s)?
- Methods: Describe possible methods to get to your desired product(s). Give all the details necessary to be able to compare the different methods. Think of the aspects given in the case description. Any choices you make should be explained.
- Recommendation: Compare your described methods. Which method would you choose at the given scale? Support the choices you make. Is there anything an investor still should consider before starting a plant on industrial scale? So give the actual advice.
- Conclusion: Summarize your advice, with naming important (dis)advantages of your advised method.
- References: List of sources used. Don't forget to reference in your text to these sources.

Remember there is no right or wrong answer, there are more ways to make one product, but always support your choices.

2.2 Draft report

2.2.1 Instructions

On the next page you can hand in your draft report. After you handed in your report, peers will give you feedback and you will have to give feedback to others.

Some suggestions for what feedback you could give:

- What is good about this report in general?
- What could be improved in this report in general? Give for example three tips.
- Do you see multiple methods to get to the desired product?
- Do you see enough support for a made decision? Do you understand a made decision?
- Is it complete? Are all the given aspects of the assignment mentioned?

2.2.2 Writing draft report

Here you can hand in your report and give feedback.

A hand-in tool and a way of ungraded peer feedback tool (maybe peer-assessment without grading?) should be placed here.

2.3 Final report

2.3.1 Using feedback

You have given feedback to your peers, but you also received some feedback. You can use this feedback to critically look to your report and see if you can improve your report. If you are satisfied with the result, you can upload your final report on the next page.

2.3.2 Writing final report

After you got feedback from your peers, you can hand in your final report here. Your report will be graded.

A hand-in tool and graded teacher assessment tool should be placed here.

2.4 Wrap up

Some information about how long grading will take and what will happen next for the credential. Maybe also information about on-campus application can be placed here.