Annex A

1. GE NEW COURSE CONTENT

Academic Year	AY2022-2023	**Semester**	2
School/Programme	School of Materials Science and Engineering Doctor of Philosophy (MSE)		
Course Coordinator	Dr Alex van Herk		
Course Code	MS7460		
Course Title	Polymer Recycling and Sustainable Polymeric Materials		
Pre-requisites	N/A		
No of AUs	2		
Contact Hours	26 (20 lecture hours, 6 tutorial hours)		
Proposal Date ***i.e. date proposal was drafted***	15 March 2022		
Expected Implementation date of new/revised course	AY2022-2023 Semester 2		
Suggested Class Size	20		
Any cross-listing? ***Is course opened to all Postgraduate students (including IGP) or specific program (please indicate)?***	Master of Engineering (MSE) Master of Science (MSE) Doctor of Philosophy (IGP) Students from the above-stated programmes are not required to seek approval from MSE to be registered for the course.		

Course Aims

1. This course is trying to achieve full awareness of the sustainability aspects of materials. This includes looking at existing materials and their ways of recycling as well as redesigning materials on formulation and molecular level.
2. The course should be taken by PhD and MEng in Materials Science and Engineering and MSc in Materials Science and Engineering that have a vested interest in sustainability of polymer materials.
3. Any professional in materials will be looking at sustainability aspects of materials, being it facilitating recycling or replacement by more sustainable alternatives. So for a future career in materials (being it in research or industry) this course is very useful.

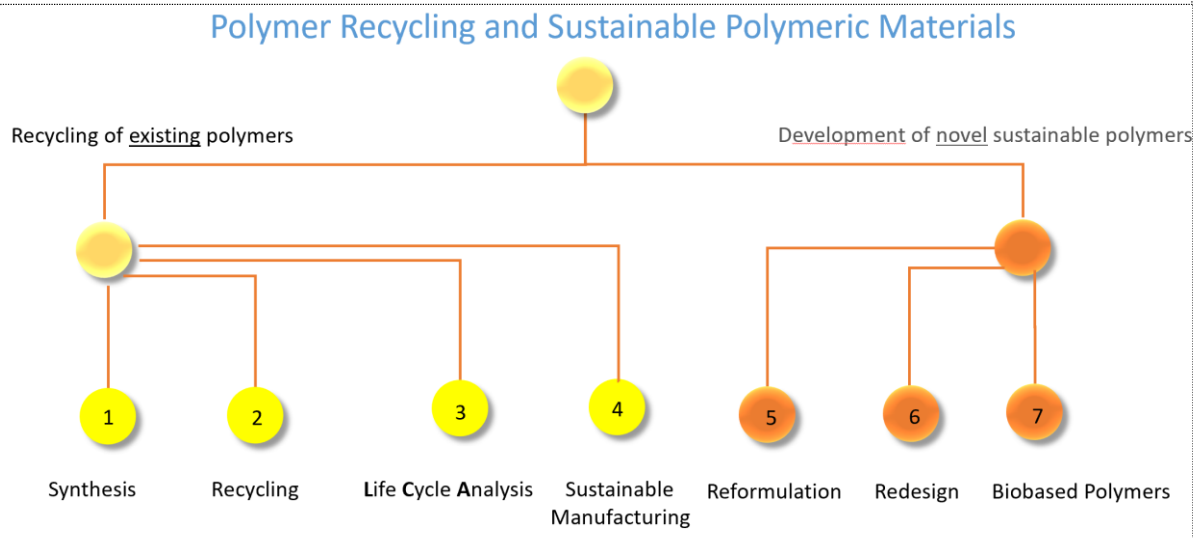
Intended Learning Outcomes (ILO)

By the end of this course, you should be able to:

1. Explain the important aspects of the polymerization mechanisms of materials.
2. Classify the main materials according to key materials properties and polymerization mechanism of formation.
3. Identify the main environmental issues with polymer waste.
4. Identify the most important aspects of polymer waste collection and sorting.
5. Explain the main aspects and current industrial applications of the four polymer recycling routes.
6. Explain the main aspects of life cycle analysis.
7. Give examples of aspects of sustainable manufacturing of materials.
8. To apply aspects of reformulation of materials to make then more sustainable.
9. To apply aspects of redesigning materials on a molecular level to make them more sustainable.

10. To explain the main biobased building blocks and biobased replacements of materials.
11. Critically read and interpret scientific literature in the area of sustainable polymeric materials.
12. Write an essay in your specific area of interest with respect to sustainable polymeric materials.

Course Content



- Materials classification
- Key materials properties
- Step-growth polymerization
- Chain-growth polymerization
- Polymerization techniques
- Environmental issues

- Collecting and sorting of materials
- Primary recycling
- Secondary/mechanical recycling with deterioration of properties and remedies
- Tertiary/chemical recycling
- Quaternary recycling (energy recovery and/or compostable materials)

- Life Cycle Analysis
- Aspects of sustainable manufacturing of materials (eg emulsion polymerization)
- Reformulation of materials for increased sustainability
  - Monomaterials
  - Additives
- Redesign of materials on molecular level
  - Thermoplastic vs thermoharders;
    Physical crosslinks (thermoplastic elastomers), reversible crosslinks (vitrimers)
  - Insertion of weak bonds
- Biobased building blocks
- Biobased materials replacements
- Discussion of scientific literature on sustainable materials
- Essay writing on sustainable materials

Assessment (includes both continuous and summative assessment)

Note: It is advised that Group component and class participation should not be more than 40% and 20% respectively, unless with good justification.

Component	ILO Tested	Weighting	Team/Individual	Assessment Rubrics
1. Continuous Assessment 1 (CA1): Quizzes (x 6)	1–10	60%	Individual	Appendix 1
2. Continuous Assessment 2 (CA2): Live Sessions – Class Participation (x 6)	1–11	20%	Individual	Appendix 2
3. Continuous Assessment 3 (CA3): Essay	12	20%	Individual	Appendix 3
Total		100%		

Formative feedback

Feedback is an important aspect to this course. You will receive both written feedback on the answers you gave in the quizzes and verbal feedback from me about your performance during the live sessions. Your final essays will be graded and extensive feedback on both scientific content and application of the elements of the course will be given.

Learning and Teaching Approach

Note: Please include and indicate TEL component.

Approach	How does this approach support you in achieving the learning outcomes?
Lecture (prerecorded)	The lecture materials are accompanied by self-practice questions, not only help to build the fundamental technical knowledge required for this course, but also help to develop your individual learning abilities and attitudes toward active learning. You may attempt the self-practice questions anytime, anywhere, and you can revisit the self-practice questions as many times as you want.
Live (video) sessions)	These sessions will allow you to ask specific questions and for the teacher to assess you understanding of the course materials. We will discuss scientific literature in the area of sustainable materials.
Essay writing	This will allow the technical knowledge acquired in this course to be applied to a topic of specific interest to the student and apply design principles from the course.

Reading and References

Introductory reading

For basics in polymer chemistry (ILO 1,2):

- Introduction to Polymers By Robert J. Young, Peter A. Lovell, chapters 1-4 or

- M. P. Stevens, Polymer Chemistry, An Introduction, chapters 1-4.

1. Chemical & Engineering News October 2019, p28; Plastic makers throw chemistry at their waste problem, A.H. Tullo
2. Nature 2021 Vol 590, p423, Closed-loop recycling of polyethylene-like materials, S. Mecking et al.
3. Environ. Sci. Technol. 2010, 44, 8264-8269. Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers, M.D. Tabone et al.
4. Resources, Conservation and Recycling Vol 145, 2019, p 67-77, LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore, Hsien H. Khoo
5. Straights Times Nov 2, 2019 Biodegradable disposables can harm environment too

Further references for some of the papers to be discussed in the live sessions

6. Science 2021, Vol. 373, No. 6550 Plastics In The Earth System. A. Stubbings Et Al.
7. 4R Sustainability, Inc. 2011 Demingling the mix: An assessment of commercially available automated sorting technology
8. IEEE SENSORS 2009 Conference p 1473 Identification of Shredded Plastics in milliseconds using Raman Spectroscopy for Recycling, Tsuchida et al.
9. Recycling 2022, 7, 11, Assessment of performance and challenges in use of commercial automated sorting technology for plasic waste. C. Lubongo and P. Alexandridis
10. A white paper from the 8th Chemical Sciences and Society Summit (CS3) 2020 Science to enable sustainable plastics
11. Grün Book – CLOSING THE WASTE LOOP THROUGH INNOVATIVE PLASTIC RECYCLING 2020
12. www.Intechopen.com 2012 Recent Advances in the Chemical Recycling of Polymers, D.S. Achilias et al.
13. Sci. Adv. 2020; 6 : eaba7599, Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation Walker et al.,
14. A*Star Research Issue 21 | January – February 2021 p 29, Thoniyot et al.
15. Macromolecules 53, 3994-4011 (2020).Degradable Poly(alkyl acrylates) with Uniform Insertion of Ester Bonds, Comparing Batch and Semibatch Copolymerizations, Lena et al.
16. J. Am. Chem. Soc. 2020, 142, 2100−2104 A Polymer with “Locked” Degradability: Superior Backbone Stability and Accessible Degradability Enabled by Mechanophore Installation, Hsu et al.
17. www.bio-based.eu/markets Bio-based Building Blocks and Polymers in the World, Pia Skoczinski, et al. Edition 2020
18. J. of Industrial Ecology 2021, 25, 1318-1337 Techno-economic assessment and comparison of different plastic recycling pathways, R. Volk et al.
19. Collias e al, Circular Economy of Polymers: Topics in Recycling (2021), Chapter 8: Life Cycle Assessment of Polymers and Their Recylcing, S. Das et al.
20. Macromol. Rapid Commun. 2021, 42, 2000415, Mechanical Recycling of Packaging Plastics, A Review, Z.O.G. Schijns, M.P. Shaver
21. Nature Reviews, Materials https://doi.org/10.1038/s41578-020-0190-4, Chemical Recycling to monomer for an ideal, circular polymer economy, G.W. Coates and Y.D.Y.L. Getzler.
22. Waste Management 105 (2020) 128-138 Technologies for chemical recycling of household plastics-A technical review and TRL assessment, M. Solis, S. Silveria
23. Prog. Energy Combust Sci., 36, 2010 103-129, The valorization of plastic solid waste by primary to quaternary routes: from re-use to energy and chemicals, S.M. Al-Salem et al.
24. Science 334, 965 (2011, Silica-like malleable materials from permanent organic networks. L. Leibler et al.

Course Policies and Student Responsibilities

1) General

You are expected to complete all assigned pre-class (live sessions) readings and activities, attend all live sessions punctually and take all scheduled assignments and quizzes by due dates. You are expected to take responsibility to follow up with course notes, assignments and course related announcements for seminar sessions they have missed. You are expected to view all pre-recorded lectures before the respective live sessions.

(2) Absenteeism

Absence from a live session without a valid reason will affect your overall course grade. Valid reasons include falling sick supported by a medical certificate and participation in NTU's approved activities supported by an excuse letter from the relevant bodies.

If you miss a live session, you must inform the course instructor via email prior to the start of the class.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Alex Van Herk	N/A	N/A	a.m.v.herk@tue.nl

Planned Weekly Schedule

Week	Topic	ILO	Readings/ Activities before respective session
Week 1	Materials classification Key materials properties Step-growth polymerization	1, 2	Refresh knowledge on step-growth polymerization.
Week 2 Modul 1	Chain-growth polymerization Live session 1 Quiz 1 (ILO 1, part of 2)	1, 2	Refresh knowledge on chain-growth polymerization.

Week 3	Chain-growth polymerization Cont'd Environmental issues Collecting and sorting of materials. Primary recycling	2, 3, 4, 5	Read refs 6, 7, 8, and 9
Week 4	Secondary/mechanical recycling with deterioration of properties and remedies Live session 2 (ILO 11) Quiz 2 (ILO 3,4)	3, 4, 5	Read refs 13, 20
Week 5	Tertiary/chemical recycling	5	Read ref 11, 12 and 22
Week 6	Quaternary recycling (energy recovery and/or compostable materials) Live session 3 (ILO 11) Quiz 3 (ILO 5)	5, 11	Read ref 23
Week 7	Life Cycle Analysis	6	Read ref 18, 19
Week 8	Life Cycle Analysis	6	Read ref 4
Week 9	Aspects of sustainable manufacturing of materials, polymerization techniques. Live session 4 (ILO 11) Quiz 4 (ILO 6)	7, 11	Do a literature search on sustainable manufacturing (including choice of additives)
Week 10	Aspects of sustainable manufacturing of materials (*example* emulsion polymerization) Reformulation of materials for increased sustainability -Monomaterials -Additives	7, 8	Read selected papers from previous session (week 9)
Week 11	Redesign of materials on molecular level; physical crosslinks, reversible crosslinks (vitrimers) Live session 5 (ILO 11) Quiz 5 (ILO 7, 8)	9, 11	Read ref 24
Week 12	Redesign of materials on molecular level -Insertion of weak bonds	9	Read ref 2, 14, 15, 16 Select you essay topic
Week 13	Biobased building blocks Biobased materials replacements Live session 6 (ILO 11) Quiz 6 (ILO 9, 10)	10	Read ref 17 Start writing the essay

Modul 2
Modul 3
Modul 4
Modul 5
Modul 6
Modul 7

Appendix 1

Quizzes

Criteria	Unsatisfactory: <40%	Borderline: 40% to 49%	Satisfactory: 50% to 69%	Very good: 70% to 89%	Exemplary: >90%
1 explain the important aspects of the polymerization mechanisms of materials	Lacks understanding of what a polymerization mechanism is. Cannot explain important aspects of polymerization mechanisms	Some understanding of what a polymerization mechanism is but cannot name them and only partially can mention important aspects.	Can classify the two main polymerization mechanisms but cannot name important aspects or only one.	Can classify the two main polymerization mechanisms and can name important aspects but misses out on one or two.	Can classify the two main polymerization mechanisms and can name all important aspects.
2 classify the main materials according to key materials properties and polymerization mechanism of formation.	Cannot mention any materials nor associate them with key materials properties. Is not able to match the materials with the polymerization mechanism of formation.	Can mention 3-4 different polymeric materials but cannot associate them with their key materials properties. Is only able to match one or two of the materials with the polymerization mechanism of formation.	Can mention 3-4 different polymeric materials and can at least for one material associate with their key materials properties. Is able to match most of the materials with the polymerization mechanism of formation.	Can mention 4 different polymeric materials and can associate the materials with most of their key materials properties. Is able to match most of the materials with the polymerization mechanism of formation.	Can mention 4 different polymeric materials and can associate with their key materials properties. Is able to match all the materials with the polymerization mechanism of formation.
3 identify the main environmental issues with polymer waste.	Does not recall any negative aspects of plastics in the environment.	Can mention one or two environmental issues but cannot give any further details.	Can mention most environmental issues but cannot give any further details.	Can mention most environmental issues and can give further details on one or two of them.	Can mention all environmental issues and can give detailed information about all of them.
4 identify the most important aspects of polymer waste collection and sorting.	Unable to identify any aspects of polymer waste collection nor polymer waste sorting.	Can identify some aspects of either polymer waste collection or sorting.	Can identify some aspects of polymer waste collection and sorting.	Can identify most aspects of polymer waste collection and sorting.	Can identify all aspects of polymer waste collection and sorting.
5 explain the main aspects and current industrial	Is not aware of the four polymer recycling routes and cannot give	Is aware of the four polymer recycling routes but not in any detail and	Is aware of the four polymer recycling routes and can give most aspects	Is aware of the four polymer recycling routes and can give most aspects	Is aware of the four polymer recycling routes and can give all aspects of

applications of the four polymer recycling routes	any examples of industrial applications of polymer recycling routes.	cannot give any examples of industrial applications of polymer recycling routes.	of those routes and can give one or two examples of industrial applications of polymer recycling routes.	of those routes and can give examples of industrial applications of most of the four polymer recycling routes.	those routes and can give examples of industrial applications of each of the four polymer recycling routes.
Criteria	**Unsatisfactory: <40%**	**Borderline: 40% to 49%**	**Satisfactory: 50% to 69%**	**Very good: 70% to 89%**	**Exemplary: >90%**
6 explain the main aspects of life cycle analysis	Unable to mention the foundations of LCA on polymers.	Able to comprehend one of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend two of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend most of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling
7 give examples of aspects of sustainable manufacturing of materials	Unable to mention any aspects of sustainable manufacturing. Is not aware of any aspects of emulsion polymerization.	Able to mention one or two aspects of sustainable manufacturing. Is not aware of any aspects of emulsion polymerization.	Able to mention one or two aspects of sustainable manufacturing. Is aware of some aspects of emulsion polymerization.	Able to mention most of the aspects of sustainable manufacturing. Is aware of main aspects of emulsion polymerization.	Able to mention the aspects of sustainable manufacturing. Is aware of all aspects of emulsion polymerization.
8 to apply aspects of reformulation of materials to make then more sustainable	Unable to read and understand materials science literature on formulations of materials. Unable to apply aspects of reformulation of materials to make them more sustainable.	Can read simple materials science literature and partially understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read simple materials science literature and understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read and understand materials science literature and understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read and understand materials science literature at a high level and understand the formulation aspects. Can apply complex aspects of reformulation of materials to make them more sustainable.
9 to apply aspects of redesigning materials on a molecular level to make them more sustainable	Unable to apply aspects of redesigning of materials on a molecular level to make them more sustainable.	Can read simple materials science literature and partially understand the molecular aspects. Can partially apply some aspects of redesigning of materials to make them more sustainable.	Can read simple materials science literature and understand the molecular aspects. Can partially apply some aspects of redesigning of materials to make them more sustainable.	Can read and understand materials science literature and understand the molecular aspects. Can fully apply some aspects of redesigning of materials to make them more sustainable.	Can read and understand materials science literature at a high level and understand the molecular aspects. Can apply complex aspects of redesigning of materials to make them more sustainable.

10 to explain the main biobased building blocks and biobased replacements of materials	Cannot mention any biobased building blocks and biobased replacement materials.	Can mention one or two biobased building blocks but cannot place them in the appropriate polymerization mechanism. Only can mention one or two biobased replacement materials. For neither of these can give further details on issues.	Can mention for each polymerization mechanism one or two biobased building blocks and can mention one or two biobased replacement materials. For neither of these can give further details on issues.	Can mention for each polymerization mechanism the main biobased building blocks and can mention multiple biobased replacement materials. Can also indicate some issues with using these.	Can mention for each polymerization mechanism the main biobased building blocks and associated challenges with using those building blocks and can mention multiple biobased replacement materials with their strengths and weaknesses.
11 critically read and interpret scientific literature in the area of sustainable polymeric materials	Unable to read and understand materials science literature in the area of sustainable polymeric materials.	Can read simple materials science literature and partially understand the sustainability aspects.	Can read simple materials science literature and understand the sustainability aspects.	Can read and understand materials science literature and understand the sustainability aspects.	Can read and understand materials science literature at a high level and understand the sustainability aspects very well.

Appendix 2

Class Participation

Standards	**Criteria**
A+ (Exceptional) A (Excellent)	Important contributions to class discussion; asks insightful questions; precisely answers questions; participates in a meaningful and constructive manner including enabling other students to contribute but does not dominate; demonstrates thoughtful ideas and opinions in a convincing manner.
A- (Very good) B+ (Good)	Meaningful contributions to class discussion; ask interesting questions; accurately answer the questions; capacity to articulate and present points of view clearly; participates in a meaningful and constructive manner; evidence of having read and assimilated the class material; Capable to demonstrate ideas and opinions in a convincing manner.
B (Average) B- (Satisfactory) C+ (Marginally satisfactory)	Some contributions to class discussion; ask some questions; some capacity to articulate and present points of view; some evidence of constructive engagement during discussion; Capable to demonstrate ideas and opinions.
C (Bordering unsatisfactory) C- (Unsatisfactory)	Minimal contributions to class discussion; ask very little questions; can answer a few questions; limited capacity to articulate and present points of view; limited evidence of constructive engagement during discussion.
D, F (Deeply unsatisfactory)	Very minimal or no contributions to class discussion; no questions; could not answer questions; no evidence of an individual viewpoint; failure to read the assigned reading; unexplained or unjustified absences from class activities.

Appendix 3

Essay (ILO 12)

Criteria	**Unsatisfactory: <40%**	**Borderline: 40% to 49%**	**Satisfactory: 50% to 69%**	**Very good: 70% to 89%**	**Exemplary: >90%**
Comprehension The ability to comprehend sustainability aspects of polymeric materials in relation to the topic of choice.	Unable to comprehend sustainability aspects of polymeric materials.	Partially comprehend some of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend some of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend most of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend the sustainability aspects of polymeric materials in relation to the topic of choice.
Application Ability to apply the relevant knowledge, principles and design aspects from the course on the topic of choice.	Unable to apply sustainability aspects of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	apply a sustainability aspect of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply 2-3 aspects of sustainability aspects as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply most of the sustainability aspects of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply all different aspects of sustainability in combination, as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.