

TECHNOLOGY & COSTS**Biorenewable Insights****Bio-based Polyamides**

Table of Contents

A Report by **NexantECA**, the Energy and Chemical Advisory company

Published Date: September 2021

www.nexanteca.com/subscriptions-and-reports**Contents**

1	Executive Summary	1
1.1	Overview.....	1
1.2	Introduction.....	1
1.3	Technologies	3
1.4	Economics	5
1.5	Capacity.....	12
1.6	Implications for the Conventional Technology	13
2	Introduction.....	14
2.1	Overview.....	14
2.2	Background	16
2.3	Polyamides Types and Monomers	16
2.3.1	Polyamides Types	16
2.3.2	Polyamide Monomers.....	17
2.4	Polyamides Production.....	19
2.4.1	Polycondensation of a Diacid and a Diamine	19
2.4.2	Polymerization of a Lactam	21
2.4.3	Polymerization of an Amino Acid	22
2.5	Properties of Polyamides	23
2.6	Commercial Applications of Polyamides	24
2.6.1	Electrical/Electronics	24
2.6.2	Automotive	24
2.6.3	Industrial.....	24
2.6.4	Consumer.....	25
2.6.5	Packaging.....	25
2.6.6	Appliances	25
2.6.7	Building and Construction	25
2.7	Bio-renewable Resources for Production of Polyamide Monomers	25
2.7.1	Castor Oil	26
2.7.2	Palm Kernel Oil	26

2.7.3	Starch	27
2.7.4	Sugar	27
2.7.5	Tallow	28
3	Technology	29
3.1	Overview.....	29
3.2	HMDA (Hexamethylenediamine).....	31
3.2.1	Background	31
3.2.2	Product Description	31
3.2.3	Genomatica GENO™ Direct Fermentation	32
3.2.4	HMDA via HMF	37
3.2.5	HMDA via Bio-Acrylonitrile	41
3.2.6	Sugar to Acrylonitrile	47
3.2.7	HMDA via Bio-Butadiene	48
3.3	Caprolactam	72
3.3.1	Genomatica GENO™ Direct Fermentation	74
3.3.2	Toray	82
3.3.3	Caprolactam via Bio-Aminocapronitrile (from Adiponitrile)	83
3.3.4	Abandoned Routes.....	85
3.4	Adipic Acid.....	93
3.4.1	Background	93
3.4.2	Product Description	93
3.4.3	Genomatica GENO™ Direct Fermentation	94
3.4.4	Abandoned Routes.....	99
3.5	Other Diamines	101
3.5.1	1,5-Pentadiazine	101
3.6	Other Diacids.....	104
3.6.1	Azelaic Acid.....	105
3.6.2	Sebacic Acid.....	108
3.6.3	Succinic Acid.....	112
3.6.4	1,12-Dodecanedioic Acid	117
3.6.5	Long Chain Diacids	120
3.7	Other Difunctional Molecules	122
3.7.1	PA11(Rislan) and 11-Aminoundecanoic Acid	122
3.7.2	Lauro lactam.....	123
4	Economics	129
4.1.1	Sources	129
4.1.2	Capital Cost Elements.....	129
4.1.3	Operating Cost Elements	133
4.2	Cost of Production Estimates	136
4.2.1	Comparative Economics by Region	136
4.2.2	Cost of Production Models	141
5	Capacity Analysis	169

5.1	Types of Developments Considered	169
5.2	Existing Capacity	170
5.2.1	11-Aminoundecanoic Acid	170
5.2.2	Azelaic Acid	170
5.2.3	Sebacic Acid	171
5.2.4	Succinic Acid	173
5.2.5	1,5-Pentadiazine and LCDAs	173
5.3	Planned Projects	174
5.3.1	11-Aminoundecanoic Acid	174
5.3.2	Caprolactam	174
5.3.3	Other Bio-Monomer Capacity	174
6	Implications for the Conventional Technology	176
6.1	Introduction(,	176
6.2	Scale and Market Penetration	177
6.2.1	Scale of Production	177
6.2.2	Market Penetration	177
6.3	Market Pull and End Uses	179
6.3.1	Carbon Intensity and Carbon-14 Accounting	180
6.4	Prices and Margins	180
Appendices		
A	References	181

Figures

Figure 1	Bio-Based Polyamides Can Help Producers Reduce Carbon Footprints	1
Figure 2	Selected Bio-Based Monomers for Several Production of Polyamides	2
Figure 3	Pathways to Bio-Based PA 6 and PA 6,6 Monomers: Caprolactam, HDMA, and Adipic Acid	3
Figure 4	Pathways to Bio-Based Other Polyamides (Besides PA 6 and PA 6,6).....	4
Figure 5	Adipic Acid Comparative Economics by Region	5
Figure 6	Caprolactam Comparative Economics by Region	6
Figure 7	HMDA Comparative Economics by Region.....	7
Figure 8	Azelaic Acid Comparative Economics by Region.....	8
Figure 9	Sebacic Acid Comparative Economics by Region	9
Figure 10	Succinic Acid Comparative Economics by Region.....	10
Figure 11	1,5-PDA Comparative Economics by Region.....	11
Figure 12	Bio-Based Polyamides Can Help Producers Reduce Carbon Footprints	14
Figure 13	Polyamides Structure of Repeat Unit	15
Figure 14	Selected Bio-Based Monomers for Several Production of Polyamides	17
Figure 15	Pathways to Bio-Based PA 6 and PA 6,6 Monomers: Caprolactam, HDMA, and Adipic Acid	29
Figure 16	Pathways to Bio-Based Other Polyamides (Besides PA 6 and PA 6,6).....	30
Figure 17	Genomatica Route to HMDA	34
Figure 18	Genomatica HMDA Block Flow Diagram	36
Figure 19	Commercial Routes to HMDA	41
Figure 20	Fixed-bed LP Production of Hexamethylene Diamine by Hydrogenation of Adiponitrile	43
Figure 21	ADN via Solutia Acrylonitrile Process.....	45
Figure 22	Trillium Renewable Chemicals Process Flow Diagram.....	48
Figure 23	Block Flow Diagram of ADN Production.....	53
Figure 24	Zone 1 Reaction Hydrocyanation of Butadiene.....	54
Figure 25	Generic Catalyst Recovery and Purification Circuit.....	56
Figure 26	Zone 2 Reaction: Isomerization of 2M3BN.....	59
Figure 27	Zone 3 Reaction: Hydrocyanation of 3PN	60
Figure 28	Zone 3 Reaction: Adiponitrile Purification	61
Figure 29	Lebedev Process – One Step Ethanol to Butadiene	66
Figure 30	Coperbo Process – Ethanol to Acetaldehyde plus Ethanol.....	68
Figure 31	Bio-Butterfly Partnership Overview.....	71
Figure 32	Genomatica Caprolactam Cellular Pathways to Caprolactam	76
Figure 33	Genomatica Caprolactam Block Flow Diagram.....	81
Figure 34	Caprolactam from Aminocapronitrile DuPont/BASF: Cyclization	84
Figure 35	Synthesis of Caprolactam via Glucaric Acid and Adipic Acid	86
Figure 36	Pathways for Adipic Acid Production.....	96
Figure 37	Genomatica Adipic Acid Block Flow Diagram	98
Figure 38	Rennovia Block Flow Diagram	100

Figure 39	Azelaic Acid from Oleic Acid.....	107
Figure 40	Formation of Sebacic Acid from Ricinoleic Acid.....	109
Figure 41	Sebacic Acid from Castor Oil.....	111
Figure 42	Biosuccinic Acid Process Overview.....	114
Figure 43	Verdezyne Block Flow Diagram	119
Figure 44	Cathay LCDA Process Block Flow Diagram	120
Figure 45	LCDA Pathway	121
Figure 46	Block Flow Diagram for the Production of Methyl Esters	127
Figure 47	Adipic Acid Comparative Economics by Region	136
Figure 48	Caprolactam Comparative Economics by Region.....	137
Figure 49	HMDA Comparative Economics by Region.....	138
Figure 50	Azelaic Acid Comparative Economics by Region.....	138
Figure 51	Sebacic Acid Comparative Economics by Region	139
Figure 52	Succinic Acid Comparative Economics by Region.....	139
Figure 53	1,5-PDA Comparative Economics by Region.....	140

Tables

Table 1	Commercially available Renewable Monomers and Polyamides.....	12
Table 2	Properties Comparison of Polyamides	24
Table 3	Fatty Acid Composition of Palm Oil	27
Table 4	Properties of Hexamethylenediamine	32
Table 5	Standard Specifications for Polymer-Grade HMDA	32
Table 6	ADN Product Mixture via Solutia Acrylonitrile Process	44
Table 7	ADN via Solutia Acrylonitrile Process Cell Design and Materials of Construction	46
Table 8	Performance and Efficiency Improvement Arc of the Lebedev Process	63
Table 9	Typical Butadiene and Byproduct Yields from Reaction Radicals	64
Table 10	Properties of Caprolactam	73
Table 11	Physical Properties of Adipic Acid	94
Table 12	Properties of 1,5-Pentanediamine	102
Table 13	Physical Properties of Azelaic Acid	105
Table 14	Physical Properties of Sebacic Acid	108
Table 15	Properties of Succinic Acid	112
Table 16	Properties of Dodecanedioic Acid	117
Table 17	Physical Properties of 11-Aminoundecanoic Acid	122
Table 18	Properties of Laurolactam	124
Table 19	Cost of Production Estimate Model for Genomatica's Adipic Acid, USGC	141
Table 20	Cost of Production Estimate Model for Genomatica's Adipic Acid, China	142
Table 21	Cost of Production Estimate Model for Genomatica's Adipic Acid, Brazil	143
Table 22	Cost of Production Estimate Model for Genomatica's Adipic Acid, Western Europe	144
Table 23	Cost of Production Estimate Model for Genomatica's Caprolactam, USGC	145
Table 24	Cost of Production Estimate Model for Genomatica's Caprolactam, China	146
Table 25	Cost of Production Estimate Model for Genomatica's Caprolactam, Brazil	147
Table 26	Cost of Production Estimate Model for Genomatica's Caprolactam, Western Europe	148
Table 27	Cost of Production Estimate Model for Genomatica's HMDA, USGC	149
Table 28	Cost of Production Estimate Model for Genomatica's HMDA, China	150
Table 29	Cost of Production Estimate Model for Genomatica's HMDA, Brazil	151
Table 30	Cost of Production Estimate Model for Genomatica's HMDA, Western Europe	152
Table 31	Cost of Production Estimate Model for Azelaic Acid, USGC	153
Table 32	Cost of Production Estimate Model for Azelaic Acid, China	154
Table 33	Cost of Production Estimate Model for Azelaic Acid, Brazil	155
Table 34	Cost of Production Estimate Model for Azelaic Acid, Western Europe	156
Table 35	Cost of Production Estimate Model for Sebacic Acid, USGC	157
Table 36	Cost of Production Estimate Model for Sebacic Acid, China	158
Table 37	Cost of Production Estimate Model for Sebacic Acid, Brazil	159
Table 38	Cost of Production Estimate Model for Sebacic Acid, Western Europe	160
Table 39	Cost of Production Estimate Model for Reverdia's Succinic Acid, USGC	161
Table 40	Cost of Production Estimate Model for Reverdia's Succinic Acid, China	162
Table 41	Cost of Production Estimate Model for Reverdia's Succinic Acid, Brazil	163

Table 42	Cost of Production Estimate Model for Reverdia’s Succinic Acid, Western Europe	164
Table 43	Cost of Production Estimate Model for Cathay’s 1,5-PDA, USGC	165
Table 44	Cost of Production Estimate Model for Cathay’s 1,5-PDA, China	166
Table 45	Cost of Production Estimate Model for Cathay’s 1,5-PDA, Brazil.....	167
Table 46	Cost of Production Estimate Model for Cathay’s 1,5-PDA, Western Europe	168
Table 47	Commercially Available Renewable Monomers and Polyamides.....	169
Table 48	Typical Properties of Polyamides	178



TECHNOLOGY & COSTS

Biorenewable Insights

The NexantECA Subscriptions' Biorenewable Insights program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. Biorenewable Insights reports are available as a subscription program or on a single report basis.

Contact Details:

Americas:

Marcos Nogueira Cesar, Vice President, Global Subscriptions and Reports
Phone: + 1-914-609-0324, e-mail: mcesar@NexantECA.com

Erica Hill, Client Services Coordinator, Subscriptions and Reports
Phone: + 1-914-609-0386, e-mail: ehill@NexantECA.com

EMEA:

Anna Ibbotson, Vice President, Sales and Marketing
Phone: +44-207-950-1528, aibbotson@NexantECA.com

Asia:

Chommanad Thammanayakatip, Managing Consultant
Phone: +66-2793-4606, email: chommanadt@NexantECA.com

NexantECA Subscriptions and Reports provide clients with comprehensive analytics, forecasts and insights for the chemicals, polymers, energy and cleantech industries. Using a combination of business and technical expertise, with deep and broad understanding of markets, technologies and economics, NexantECA provides solutions that our clients have relied upon for over 50 years.

Copyright © 2000-2021 NexantECA (BVI) Limited. All rights reserved