Review Article

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Use of glycerol waste in lactic acid bacteria metabolism for the production of lactic acid: State of the art in Poland

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Abstract: Lactic acid is a naturally existing organic acid, which may be used in many different branches of industrial application. It can be made in the sugar fermentation process from renewable raw lactic acid, which is an indispensable raw material, including in the agricultural, food, and pharmaceutical industries. It is an ecological product that has enjoyed great popularity in recent years. In 2010, the US Department of Energy published a report about lactic acid to be a potential building element for future technology, whose demand grows year by year. The lactic acid molecule naturally exists in plants, microorganisms, and animals and can also be produced by carbohydrate fermentation or chemical synthesis from coal, petroleum products, and natural gas. In industry, lactic acid can be produced by chemical synthesis or fermentation. Although racemic lactic acid is always produced chemically from petrochemical sources, the optically pure L(+)− or D(−)− lactic acid forms can be obtained by microbial fermentation of renewable resources when an appropriate microorganism is selected. Depending on the application, one form of optically pure LA is preferred over the other. Additionally, microbial fermentation offers benefits including cheap renewable substrates, low production temperatures, and low energy consumption. Due to these advantages, the most commonly used biotechnological production process with the use of biocatalysts, i.e., lactic acid bacteria. The cost of raw materials is one of the major factors in the economic production of lactic acid. As substrate costs cannot be reduced by scaling up the process, extensive research is currently underway to find new substrates for the production of LA. These searches include starch raw materials, lignocellulosic biomass, as well as waste from the food and refining industries. Here, the greatest attention is still drawn to molasses and whey as the largest sources of lactose, vitamins, and carbohydrates, as well as glycerol—a by-product of the biodiesel component production process. Focusing on the importance of lactic acid and its subsequent use as a product, but also a valuable raw material for polymerization (exactly to PLA), this review summarizes information about the properties and applications of lactic acid, as well as about its production and purification processes. An industrial installation for the production of lactic acid is only planned to be launched in Poland. As of today, there is no commercial-scale production of this bio-raw material. Thus, there is great potential for the application of the lactic acid production technology and research should be carried out on its development.

Keywords: lactic acid, lactic acid bacteria, waste management, glycerol, circular economy

1 Introduction

Circular economy (CE) is the trend in engineering that improves the development of technology to maximize the exploitation of resources and make them recyclable [1–3]. This tendency is observed also in fuels and energy management, especially in renewable resources of fuels and energy [4]. The term circular economy covers the steps of recycling in which technology should preserve the resources or prevent waste production; design of product making possible to reuse parts of the product, possibly the whole product; and recycle material or finally (and at least) energy recycling of flammable residues [5–8]. The last opportunity could be widened by the other technologic options like gasification of organic residues to a kind of syngas and use it for energy production in a fuel cell [9–11]. Increasing attention to renewable energy resources is given in recent years, among others to the

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production of renewable liquid fuels. One significant example of fermentation usage is the production of alcohols and to further extend ethers as a substitute (or add-on) of gasoline in tropical and mild climate regions, respectively [12–17]. Even etherification of glycerol is regarded as a possibility for automotive renewable fuel production [18,19]. Anaerobic digestion is used for biogas production as a biofuel but possibilities of its usage are significantly higher in biofuel production and by-products utilization [20–24]. Many strategies for a circular economy are met in engineering and management. Thus, recovery of additional commercial goods from the process of organics production (among other fuels) is an important prospect in the point of view of the circular economy [25–28]; in the focus of the authors are bioprocesses used in renewable fuel production. Some of those processes are waste-less or with minimal by-product generation (e.g., the conversion of bioethanol to bioether) but in some other processes by-products generation is significant (e.g., fatty acids conversion to FAME with glycerol formation). Waste biomass is transformed into many commercial products by several physicochemical or biological processes applying the rules of green chemistry [29]. The first step is to recover the secondary raw materials. Next, the most appropriate way for biomass recycling is the refining of secondary biocomponents for further processes and then using other steps of recycling. Figure 1 illustrates the idea of biorefinery for waste biomass.

Boldface arrows on the chart (Figure 1) represent primary processes of biomass wastes or by-product treatment while the slender ones describe secondary processes. Both bioprocesses and classic physicochemical treatment are used in bio-refining or fuels and energy recovery. In biotechnology, fermentation plays a special role and often is associated with hydrolysis as pre-processing [30,31]. Fermentation leads to the production of bioethanol [13,32,33], biogas [20,21,34,35], hydrogen from dark fermentation [36,37], as well as biomass reforming for fuel cell purpose [38]. In classic physicochemical processes, preliminary processing leads to syngas, and in secondary processes hydrocarbons are produced by catalytic synthesis [39,40]. Moreover, syngas could be used as a substrate for fermentation toward alcohols and organic acids [41,42]. Another classic processing process is pyrolysis, which could yield solid carbonizate – char, pyrolytic gases, and pyrolysis oil containing a mixture of organic compounds. Char has possible application as an adsorbent, pyrolytic gases as fuel, and some chemicals could be separated from pyrolysis oil (e.g., limonene) or hydrocarbons are produced by hydrotreating [43–45].

Finally, the focus of this paper is the processing of biofuels, specially FAME. Glycerol is a by-product of the transesterification of fatty acids [46]. In the classic

Figure 1: The idea of components or energy recovery from bioprocesses waste or by-product. Descriptors: (1) fermentation, (2) hydrolysis, (3) pyrolysis, (4) outgasification, (5) combustion, (6) reforming (hydro-reforming), and (7) catalytic synthesis.
approach, the alkali catalyst is used but recent trends are to use enzymes, e.g., lipase [47]. Such an approach makes the process more renewable and eco-friendly because all substrates are from biological sources. The aim is to make the process even more efficient and eco-friendly at every stage of the processing of main and by-products. One of the possible solutions that are currently being considered is the biorefining of glycerol as a by-product of biocomponent production for diesel fuel [48,49].

Some value-added chemicals could be produced from glycerol, among others: succinic acid [50], hydrogen in the hydrothermal conversion of acrolein [51], and lactic acid [52]. In particular, the role of lactic acid has been growing in recent years in many applications ranging from food processing, through cosmetics, medicine, and ending with typically engineering applications such as the production of lactic acid polymer (PLA) and its subsequent use as a biodegradable additive to other materials, production of filaments for printers, and 3-D and prototyping various goods [6,53,54].

2 Catalytic methods of lactic acid production from glycerol

Scientists or engineers use different strategies for lactic acid production from glycerol applying chemical reactions with different kinds of catalysts or biotechnology methods utilizing microorganisms of a different kind, including GMO ones. Komanoya et al. propose a combined catalyst with Pt nanoparticles and TiO₂ as an effective improvement of reaction with 63% yield [55]. Yin et al. elaborated graphite-based catalyst with NiO nanoparticles, which improve the selectivity of reaction up to 97.6% in an alkaline water solution of glycerol [56]. Another team with the same leader (Yin-Zhang et al.) developed a series of Cu-based catalysts (Cu/hydroxyapatite, Cu/MgO, Cu/ZrO₂) resulting in 91% conversion of glycerol and 90% selectivity toward lactic acid [57]. A similar idea followed the team of Moreira et al.; they produced a series of catalysts using copper and based on Al₂O₃, ZnO, or MgO also in an alkaline glycerol solution [58]. The team of Arcano et al. tested an activated carbon catalyst with noble metals deposited on 5% Pt/C and 10% Pd/C giving 99% glycerol conversion with 68 and 74% selectivity, respectively [59]. Noble metals were used as active material on activated carbon by Zhang et al. with mild alkali solution; LiOH, KOH, NaOH, and Ba(OH)₂ were tested and they conclude that many variants of conditions play role in the conversion to lactic acid with selectivity from 69.3 to 100% [60]. Yang et al. developed zirconia-supported copper oxide catalysts (CuO/ZrO₂) and depending on the composition they even obtained 100% glycerol conversion with 94.6% selectivity to lactic acid [61]. A different approach was presented by Rodrigues et al. also using an alkaline medium for conversion, while NaOH and KOH were used as catalysts and the reaction reached 97% efficiency [62]. Only selected technologies for the catalytic conversion of glycerol to lactic acid are presented above. The latest research introduces further modifications to the catalysts: Cu on CaO/MgO [63], zirconium–cerium oxides/SBA-15 [64], Au/bentonite [65], Ni–NiOₓ [66], Au/hydroxyapatite/BN [67], and research is still in progress.

All chemical methods of converting glycerol have a common disadvantage of the necessary energy input since most of the reactions were carried out at elevated temperatures. Biotechnological methods do not require additional energy for the reaction and are carried out under moderate temperature conditions. Unfortunately, the degrees of glycerol conversion in biochemical methods are usually much lower, and at the same time require glycerol dilutions. However, in the point of view of green chemistry, biotechnological processes of glycerol conversion are more environmentally friendly [29].

However, a review of biotechnology methods for glycerol conversion to lactic acid is the purpose of this publication and is presented in the following section.

3 Lactic acid production by biotechnological methods

The chemical synthesis of the commercial process is based on laconitrite and this process occurs in the liquid phase at high atmospheric pressure [68–70,73]. This process has many steps to produce lactic acid and is represented by the following reactions:

\[
\text{CH}_3\text{CHO} + \text{HCN} \xrightarrow{\text{HCl}} \text{CH}_3\text{CHOH-CN} \quad \text{(Acetaldehyde)}
\]

\[
\text{CH}_3\text{CHOH-CN} + 2\text{H}_2\text{O} \xrightarrow{\text{HCl}} \text{CH}_3\text{CHOH-CONH}_4 \quad \text{(Ammonium lactate)}
\]

A chemical reaction to lactic acid production.

This chemical synthesis yields a racemic mixture of lactic acid. Musashino, Japan, and Sterling Chemicals
Inc., USA, are using this technology on the fabric procedure. The next options are base-catalyzed degradation of sugars, the reaction of acetaldehyde, oxidation of propylene glycol, carbohydrate fermentation, and many others [84,85,90].

Fermentation is the best option to provide an ecological and economical biotechnological process. A batch reactor, a half-batch reactor, and a reactor with repeated dosing of feedstock, and a continuous reactor are the most frequently used reactors in the production of lactic acid. The higher concentration of lactic acid has been tested and is obtained in cultures using a batch reactor and semi-batch reactor, while higher productivity is obtained by a continuous reactor. Reports in the literature state that the latest biotechnological research on lactic acid differs in fermentation and process methods and process parameters [71,72,82,83].

The parameters responsible for the fermentation are temperature, flow rate, pressure, mixing, pH, and oxygenation [78–81]. These factors are the most important and of great influence to process because they indicate productivity, selectivity, and yield of a reaction [77,89].

The most important, however, is the selection of microorganisms for the fermentation process, which may affect the technological regime and the profitability of the process. Currently, many microorganisms useful for the production of lactic acid have already been identified, and further applications and optimization of current processes are also being worked out [86–88]. Exemplary cultures of microorganisms used in the production of lactic acid are presented in Table 1.

Various substrates are taken into account for the production of lactic acid. Screening shows that for a given substrate, a specific microorganism or a set of microorganisms can be selected for optimal processing of the raw material into lactic acid. The choice of substrates with selected microorganisms is presented in Table 2.

The use of alternative substrates in fermentation processes, aiming at the utilization of agricultural low-cost raw materials or by-products from various industries (molasses, bran, corn syrup, whey, etc.) lowers the cost of the culture medium used and hence the final product [74,75,91]. However, these substrates have complex compositions whose exact total is often unknown. In addition to the carbon source and other nutrients, some compounds that may be present or even formed during the process steps, as pre-treatment, may be factors capable of inhibiting the growth of microorganisms or prevent the synthesis of the metabolite of interest [70,92,97].

The most commonly used substrate for Lactobacillus (L.) rhamnosus ATCC 10863 fermentation for lactic acid production is glucose, but cellulose, lignocellulose, and sucrose are also used. Molasses hydrolyzed can also be used and, in this work, the lactic acid production with this cheap and green substrate without a pre-treatment will be explored [76,77,95,96,98].

Along with the growing interest in biocomponents for diesel fuels, a large amount of glycerol appears in the market. It is used in many industries, as an additive to cosmetics or as fuel. An interesting direction in the processing of this by-product would be its transformation into lactic acid as a chemical raw material. Currently, there is little information in the literature on the biotechnological conversion of glycerol to lactic acid, and hence, the authors’ interest in the development and optimization of this method. In particular, in Poland, there will also be an increase in the production of biocomponents, and thus glycerol, as a result of the adjustment to the EU policy.

### Table 1: Example of yield, productivity, and quantity of lactic acid microbial production [83]

| Microorganism               | Concentration (g/L) | Yield (g/g) | Productivity (g/L h) |
|-----------------------------|---------------------|-------------|----------------------|
| Rhizopus oryzae ATCC 52311  | 83.0                | 0.88        | 2.6                  |
| Rhizopus oryzae NRRL 395    | 104.6               | 0.87        | 1.8                  |
| Enterococcus faecalis RKY1  | 144.0               | 0.96        | 5.1                  |
| Lactobacillus rhamnosus ATCC 10863 | 67.0           | 0.84        | 2.5                  |
| Lactobacillus helveticus ATCC 15009 | 65.5          | 0.66        | 2.7                  |
| Lactobacillus bulgaricus NRRL B-548 | 38.7          | 0.90        | 3.5                  |
| Lactobacillus casei NRRL B-441 | 82.0            | 0.91        | 5.6                  |
| Lactobacillus plantarum ATCC 21028 | 41.0           | 0.97        | 1.0                  |
| Lactobacillus pentosus ATCC 9041 | 21.8           | 0.77        | 0.8                  |
| Lactobacillus amyloplius GV6  | 76.2                | 0.70        | 0.8                  |
| Lactobacillus delbrueckii NCIMB 8130 | 90.0            | 0.97        | 3.8                  |
| Lactococcus lactis ssp. Lactis IFO 12007 | 90.0         | 0.76        | 1.6                  |
4 The potential of lactic acid production from biofuel by-product in Poland

Poland produces about one million tonnes of biodiesel annually in 2020 and will increase significantly until 2030. In addition, Poland is expected to increase from 10% under the biodiesel obligation to 20% by 2030. An increase in biodiesel production is therefore related to inevitable abundance of glycerol as by-product. That increased amount of crude glycerol must be used for increasing efficiency of biodiesel industry by introducing new pathways for circular economy, e.g., lactic acid production. Consequently, almost the entire industry uses only refined glycerol as raw material, as unrefined glycerol has become a potential environmental pollutant. Puriﬁcation of glycerol is a much more costly process, and the low process level obtained recently made it economical. For the sustainability of the biodiesel industry, it is important to ﬁnd a viable and efﬁcient solution to converting waste glycerol into valuable products. Alternative oil handling solution of waste glycerol is transforming it into a more valuable product, for example, lactic acid [72,99,100,105].

In Poland, over a million tonnes of biofuels are already used. They help to reduce emissions in transport, and is expected to grow in the coming years. The share of renewable energy in Polish transport is not optimistic – it is far from the requirements of 2020 and lower than the EU average, mainly due to the fact that Poland probably will not meet the EU renewable energy target for later years. But, the result only improves with biofuels. Over one million tons of biofuels were used with almost 25 million tons of total oﬃcial consumption of liquid fuels. Importantly, the use of “advanced” biofuels, for example, from waste, which counts twice in EU statistics, has ﬁnally increased [109,110].

According to the data from Trend Economy about open access to data on the import and export of molasses and glycerol as raw materials in the production of lactic acid, the information is presented in Table 3.

The value of glycerine exports from Poland shows the large possibilities of processing this by-product. The balance of exports against imports shows the overproduction of glycerol, which could be transformed into other valuable products, e.g., lactic acid.

Two years back, it turned out that the share of renewable energy sources in transport, instead of growing was decreasing. This is due to the fact that after the elimination of the gray economy, fuel consumption increased rapidly, which did not translate into biofuels. In 2018, however, something changed. The share of biofuels in transport increased by more than a half, and the share of renewable energy sources was 5.63% – the Central Statistical Oﬃce reported in 2018 [93,101,103].

**Table 2: Examples of cheap and popular waste material for feedstock application in producing lactic acid biotechnologically [83]**

| Substrate          | Organism                        | Concentration (g/L) | Productivity (g/L h) |
|--------------------|---------------------------------|---------------------|----------------------|
| Molasses           | Lactobacillus delbrueckii NCIMB 8130 | 90.0                | 3.8                  |
|                    | Enterococcus faecalis RKY1      | 95.7                | 4.0                  |
| Rye                | Lactobacillus paracasei No. 8   | 84.5                | 2.4                  |
| Sweet sorghum      | Lactobacillus paracasei No. 8   | 81.5                | 2.7                  |
| Wheat              | Lactobacillus paracasei No. 8   | 106.0               | 3.5                  |
| Wheat              | Enterococcus faecalis RKY1      | 106.0               | 1.0                  |
| Corn               | Enterococcus faecalis RKY1      | 102.0               | 4.8                  |
| Corn               | Lactobacillus amylovorus ATCC 33620 | 10.1               | 0.8                  |
| Cassava            | Lactobacillus amylovorus ATCC 33620 | 4.8               | 0.2                  |
| Potato             | Lactobacillus amylovorus ATCC 33620 | 4.2               | 0.1                  |
| Rice               | Lactobacillus casei NRRL B-441  | 162.0               | 3.4                  |
| Barley             | Lactobacillus amylophilus GV6   | 27.3                | 0.3                  |
| Cellulose          | Lactobacillus coryniformis ssp. torquens ATCC 2560 | 24.0 | 0.5 |
|                    | Rhizopus sp. MK-96-1196         | 24.0                | 0.3                  |
| Corncob waste paper| Lactobacillus coryniformis ssp. torquens ATCC 2560 | 23.1 | 0.5 |
|                    | Rhizopus orizae NRRL 395       | 49.1                | 0.7                  |
| Wood               | Lactobacillus delbrueckii NRRL B-445 | 108.0              | 0.9                  |
| Wood               | Enterococcus faecalis RKY1      | 93.0                | 1.7                  |
| Wood               | Lactobacillus helveticus R2111 | 66.0                | 1.4                  |
| Whey               | Lactobacillus casei NRRL B-441  | 46.0                | 4.0                  |
Table 3: Import and export of glycerol in the world (chosen country) in 2019 [115]

| Country       | Glycerol, glycerol waters, glycerol lyes | Exports | Imports |
|---------------|-----------------------------------------|---------|---------|
|               | Value (US$) | World share (US$) | Value (US$) | World share (US$) |
| Indonesia     | 123,269,715 | 26.97 | 881,140 | 0.15 |
| Brasil        | 48,776,123  | 10.67 | 79,709  | 0.01 |
| Spain         | 35,369,146  | 7.73  | 2,606,929 | 0.44 |
| Germany       | 33,369,146  | 7.32  | 44,083,259 | 7.57 |
| France        | 30,175,005  | 6.60  | 2,099,318 | 0.36 |
| Malaysia      | 22,992,707  | 5.03  | 22,766,139 | 3.91 |
| Netherlands   | 20,894,871  | 4.57  | 34,310,242 | 5.89 |
| USA           | 18,754,794  | 4.10  | 9,296,641 | 1.59 |
| Argentina     | 12,691,168  | 2.77  | 1,587    | 0.00 |
| Poland        | 12,649,298  | 2.76  | 343,016  | 0.05 |
| Belgium       | 12,524,594  | 2.74  | 13,917,475 | 2.39 |
| Thailand      | 10,066,763  | 2.20  | 1,334,636 | 0.22 |
| Portugal      | 7,064,742   | 1.54  | 127,995  | 0.02 |
| Canada        | 6,086,080   | 1.33  | 3,328,951 | 0.57 |
| United        | 5,375,405   | 1.17  | 17,869,989 | 3.07 |
| Kingdom       | 5,330,001   | 1.16  | 8,091    | 0.00 |
| Colombia      | 5,233,883   | 1.14  | 1,477,898 | 0.25 |
| Czech         | 4,637,885   | 1.01  | 5,264,982 | 0.90 |
| Republic      | 4,057,010   | 0.88  | 23,110,723 | 3.97 |
| India         | 4,013,475   | 0.87  | 109,713  | 0.01 |
| Romania       | 3,612,292   | 0.79  | 75,553   | 0.01 |
| Lithuania     | 3,498,359   | 0.76  | 28,357   | 0.00 |

Note: Bold row in Table signs the situation in Poland as a country regarded in the title of paper.

Nowadays, the market of the biofuels industry and waste management is huge. The policy of the fuels market is complicated but the market forecasts show quite good statistics of the growing demand for biofuels, and hence, the growing waste market.

Optimized, effective waste management is integral to petroleum refinery operations. It helps minimize risk to both people and the environment, enhances resource utilization, and can also reduce costs. Many countries have detailed legislative requirements and control systems that apply to all aspects of waste management, while others have less regulatory oversight and guidance [69,94,103,104].

Petroleum refineries generate one of the most important categories of waste – process waste. Refineries produce industrial process wastes that are inherent to the activities they carry out in the handling and processing of crude petroleum and petroleum products [102,106,107].

5 Investigated method for use of LAB

A few studies by Polish scientists so far have not shown the daily calculations and the transformation into large-scale technology. Research groups are investigating this matter; however, it is a fresh topic in Poland. Additionally, numerous worldwide studies show how important is the subject of ecological changes.

The world production of lactic acid is estimated at around 520 thousand tons per year. So far, lactic acid has not been produced in Poland, and its shortage in the entire region of Central and Eastern Europe forced the recipients of this raw material to import from Asia and Western Europe [93,108].

A project led by polish researchers implement the first installation in Poland operating on the basis of an innovative technology for the production of lactic acid using waste from agri-food and biorefinery industry. Lactic acid has a key role in the production of the most popular, fully biodegradable polymer, polylactide (PLA), used among others for the production of biodegradable packaging. PLA has a number of applications in the construction industry, technology, optics, and the automotive industry, and due to its properties, including transparency, it is also used in the production of photovoltaic cells, as well as in medicine and pharmacy, where it is used for the production of implants, screws, and surgical threads [111–114].

First of all, lactic acid bacteria metabolism has to be studied. The research plans include screening the microorganisms for the best, most economical bacteria as a biocatalyst. In addition, the catalyst used in the biotechnological process should have a low-cost financial outlay, i.e., process parameters. To judge this, a series of studies must be conducted showing possible pathways to the process. Subsequently, the fermentation process itself, first on a laboratory scale, and then in large-scale production with the proposed purification process will be conducted. According to world studies, the purification stage is the most expensive. However, to sum up, and taking into account the advantages and disadvantages – knowing that waste can be used, the treatment process can be covered by the lower energy consumption of the process than the one carried out with the chemical method.

We are currently testing three LAB species in our laboratory: Lactobacillus plantarum, Lactobacillus rhamnosus, and Lactobacillus leichmanii. Preliminary studies show great difficulty in cultivating any LAB species on
pure glycerin. Therefore, we decided to mix raw glycerin in a water solution with other waste materials like molasses. The results currently obtained do not yet allow the process to scale, but are promising. The concentration of glycerin in the aqueous solution must not exceed 5%; otherwise, there is a strong toxic effect on LAB. We tested various concentrations of glycerol up to 5% in solutions, as well as other natural waste substances, e.g., molasses or fruit peels. There is an increase in the concentration of lactic acid and a decrease in the concentration of glycerol. Lactic acid concentration is measured by using an iron chemical complex and UV-Vis spectrophotometer.

The use of molasses as a co-reactant is justified as it is also a waste material with high availability, especially it is also a precursor for the production of glycerin by chemical means. The presence of sugar-rich molasses in a mixture with glycerin should increase the efficiency of the lactic acid fermentation process, as suggested by preliminary experiments by using food waste or with the addition of molasses. Molasses is a by-product of sugar production. It was chosen by the authors as the second substance for processing into lactic acid for the comparison of processes. Figure 2 presents the change in the molasses trade balance in Poland.

These data show a huge problem with waste management but also an advantage to scientists who care about human resources and petrochemical processes and develop the biotechnology war for molasses transformation into lactic acid.

The glycerin fermentation procedure with the addition of molasses or food waste requires further development. The team plans to publish the results of ongoing experiments soon.

6 Summary

The uses for glycerol waste continue to expand. The above examples show the valuable products obtainable from this process. It is still a research topic that remains largely untapped. An additional aspect is the development of more and more common white biotechnology. In this field of science, microorganisms are used that are involved in the creation of many valuable chemical products. Biotechnological methods largely prevail over chemical methods. The basis is the possibility of avoiding the disadvantages resulting from the use of catalysts or the purification and preparation of the raw material. This significantly reduces the cost of technology and contributes to conscious waste management. Moreover, this pathway stays in accordance with green chemistry or circular economy, where every product is used in an optimized way and sustainable to the environment.

The preliminary results of the team’s laboratory test indicate the possibility of using LAB to convert glycerol or molasses to lactic acid, but the procedure still needs to be developed and optimized, first on a laboratory scale, and then also on an industrial scale.

An industrial installation for the production of lactic acid is only planned to be launched in Poland [117]. As of today, there is no commercial-scale production of this bio-raw material. Thus, there is great potential for the application of the lactic acid production technology and research should be carried out for its development.

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References

[1] Stahel WR. The circular economy. Nature. 2016;531:435–8.
[2] Minson AJ. Circular economy. Indian Conc J. 2020; 94:19–23.
[3] Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The circular economy – a new sustainability paradigm? J Clean Prod. 2017;143:757–68.
[4] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl. 2017;127:221–32.
[5] Marsac P, Van den bergh W, Piérard N, Grenfell J, Gabet T, Mouillet C, et al. Recycling. RILEM state-of-the-art reports, vol. 24. Cham: Springer, 2018. p. 203–37. doi: 10.1007/978-3-319-71023-5_5.
[6] Nishimura I. Strategy for plastics in a circular economy. Seikai-Kakou. 2018;30:577–80.
[7] Bocken NMP, de Pauw I, Bakker C, van der Grinten B. Product design and business model strategies for a circular economy. J Ind Prod Eng. 2016;33:308–20.
[8] Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod. 2016;114:1–32.
[9] Saidi M, Ghaffari A. Waste management. Design and operation of solid oxide fuel cells: the systems engineering vision for industrial application. Woodhead Publishing Series in Energy, 2019. p. 395–444.
[10] Mirowski T. Utilization of biomass for energy purpose versus reduction of emission of air pollutants from municipal and households sector. Roczn Ochr Środowiska [Internet]. 2016;18(1):466–77. Available from: http://www.ros.edu.pl/ images/roczniki/2016/028 ROS_V18_R2016.pdf
[11] Mirowski T, Mokryczki E. Thermochemical processing of solid biomass. In: Biomass in small-scale energy applications: theory and practice. In: Szubel M, Filipowicz M, editors. Energy systems: from design to management. Boca Raton: Taylor & Francis, CRC Press; 2019. p. 1–18.
[12] Saini JK, Saini R, Tewari L. Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments. 3 Biotech. 2015;5:337–53.
[13] Aditiya HB, Mahlia TMI, Chong WT, Nur H, Sebayang AH. Second generation bioethanol production: a critical review. Renew Sustain Energy Rev. 2016;66:631–53.
[14] Mohd Azhar SH, Abdullah R, Jambo SA, Marbawi H, Gansau JA, Mohd Falk AA, et al. Yeasts in sustainable bioethanol production: a review. Biochem Biophys Rep. 2017;10:52–61.
[15] Awad OI, Mamat R, Ibrahim TK, Hammid AT, Yusri IM, Hamidi MA, et al. Overview of the oxygenated fuels in spark ignition engine: environmental and performance. Renew Sustain Energy Rev. 2018;91:394–408.
[16] Rodríguez-Ántón LM, Gutierrez-Martín F, Doce Y. Physical properties of gasoline, isobutanol and ETBE binary blends in comparison with gasoline ethanol blends. Fuel. 2016;166:73–8.
[17] Awad OI, Mamat R, Ali OM, Sidik NAC, Yusaf T, Kadirgama K, et al. Alcohol and ether as alternative fuels in spark ignition engine: a review. Renew Sustain Energy Rev. 2018;82:2586–605.
[18] Meler JA, Vicente G, Paniagua M, Morales G, Muñoz P. Etheronization of biodiesel-derived glycerol with ethanol for fuel formulation over sulfonic modified catalysts. Bioresour Technol. 2012;103:142–51.
[19] Ayoub M, Khayoon MS, Abdullah AZ. Synthesis of oxygenated fuel additives via the solventless etherification of glycerol. Bioresour Technol. 2012;112:308–12.
[20] Laiq Ur Rehman M, Iqbal A, Chang CC, Li W, Ju M. Anaerobic digestion. Water Environ Res. 2019;91:1253–71.
[21] Meegoda JN, Li B, Patel K, Wang LB. A review of the processes, parameters, and optimization of anaerobic digestion. Int J Environ Res Public Health. 2018;15(10):2224.
[22] Ward AJ, Lewis DM, Green FB. Anaerobic digestion of algal biomass: a review. Algal Res. 2016;5:204–14.
[23] Fagbohungbe MO, Herbert BM, Hurst L, Ibeto CN, Li H, Usmani SQ, et al. The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. Waste Manag. 2017;61:236–49.
[24] Kleerebezem R, Joosse B, Rozendal R, Van, Loosdrecht MCM. Anaerobic digestion without biogas? Rev Environ Sci Biotechnol. 2015;14:787–801.
[25] Morseletto P. Targets for a circular economy. Resour Conserv Recycl. 2020;153:104553.
[26] Singh J, Ordoñez I. Resource recovery from post-consumer waste: important lessons for the upcoming circular economy. J Clean Prod. 2016;134:342–53.
[27] Kalmykova Y, Sadagopan M, Rosado L. Circular economy – from review of theories and practices to development of implementation tools. Resour Conserv Recycl. 2018;135:190–201.
[28] Linguori R, Faraco V. Biological processes for advancing lignocellulosic waste bioenergy by advocating circular economy. Bioresour Technol. 2016;215:13–20.
[29] Sheldon RA. Green chemistry, catalysis and valorization of waste biomass. J Mol Catal A Chem. 2016;422:3–12.
[30] Binder JB, Raines RT. Fermentable sugars by chemical hydrolysis of biomass. Proc Natl Acad Sci USA. 2010;107:4516–21.
Kucharska K, Rybarczyk P, Holowacz I, Łukajtis R, Glinka M, Kamiński M. Pretreatment of lignocellulosic materials as substrates for fermentation processes. Molecules. 2018;23(11):2937.

Zabed H, Sahu IN, Suely A, Boyce AN, Faruq G. Bioethanol production from renewable sources: current perspectives and technological progress. Renew Sustain Energy Rev. 2017;71:475–501.

Jambo SA, Abdulla R, Mohd Azhar SH, Marbawi H, Gansau JA, Ravindra P. A review on third generation bioethanol feedstock. Renew Sustain Energy Rev. 2016;65:756–69.

Sadh PK, Duhan S, Duhan JS. Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioreourr Bioprocess. 2018;5:1.

Achinas S, Achinas V, Euerink GJW. A technological overview of biogas production from biowaste. Engineering. 2017;3:299–307.

Arimi MM, Knodel J, Kiprop A, Namango SS, Zhang Y, Geißen SU. Strategies for improvement of biohydrogen production from organic-rich wastewater: a review. Biomass Bioenergy. 2015;75:101–18.

Łukajtis R, Holowacz I, Kucharska K, Glinka M, Rybarczyk P, Przyjazny A, et al. Hydrogen production from biomass using dark fermentation. Renew Sustain Energy Rev. 2018;91:665–94.

Vasileiadis S, Ziaka-Vasileiadou Z. Biomass reforming process for integrated solid oxide-fuel cell power generation. Chem Eng Sci. 2004;59:4853–9.

Jahangiri H, Bennett J, Mahjoubi P, Wilson K, Gu S. A review of advanced catalyst development for Fischer-Tropsch synthesis of hydrocarbons from biomass derived syn-gas. Catal Sci Technol. 2014;4:2210–29.

De Tissera S, Köpke M, Simpson SD, Humphreys C, Minton NP, Dürre P. Syngas biorefinery and syngas utilisation. Adv Biochem Eng Biotechnol. 2019;166:247–80.

Phillips JR, Huhnke RL, Atiyeh HK. Syngas fermentation: a microbial conversion process of gaseous substrates to various products. Fermentation. 2017:3:28.

Sun X, Atiyeh HK, Huhnke RL, Tanner RS. Syngas fermentation process development for production of biofuels and chemicals: a review. Bioreourr Technol Rep. 2019;7:100279.

Cheng K, Kang J, King DL, Subramanian V, Zhou C, Zhang Q, et al. Advances in catalysis for syngas conversion to hydrocarbons. Adv Catal. 2017;152:125–208.

Zhou W, Cheng K, Kang J, Zhou C, Subramanian V, Zhang Q, et al. New horizon in C1 chemistry: breaking the selectivity limitation in transformation of syngas and hydrogenation of CO₂ into hydrocarbon chemicals and fuels. Chem Soc Rev. 2019;48:3193–228.

Ward J, Rasul MG, Bhuinya MMK. Energy recovery from biomass by fast pyrolysis. Procedia Eng. 2014;90:669–74.

Talha NS, Sulaiman S. Overview of catalysts in biodiesel production. ARPN J Eng Appl Sci. 2016;11:439–48.

Aminiz I, Ilham Z, Ong HC, Mazaheri H, Chen WH. State of the art and prospective of lipase-catalyzed transesterification reaction for biodiesel production. Energy Convers Manag. 2017;141:339–53.

Valero O, Misra M, Mohanty AK. Poly(glycerol-co-diacids) polyesters: from glycerol biorefinery to sustainable engineering applications, a review. ACS Sustain Chem Eng. 2018;6:5681–93.

Lari GM, Pastore G, Haus M, Ding Y, Papadokonstantakis S, Mondelli C, et al. Environmental and economical perspectives of a glycerol biorefinery. Energy Environ Sci. 2018;11:1012–29.

Sadhuksan S, Villa R, Sarkar U. Microbial production of succinic acid using crude and purified glycerol from a Crotalaria juncea based biorefinery. Biotechnol Rep. 2016;10:84–93.

Long YD, Fang Z. Hydrothermal conversion of glycerol to chemicals and hydrogen: review and perspective. Biofuel Bioprod Biorefin. 2012;6:686–702.

Bagheri S, Julkapli NM, Yehye WA. Catalytic conversion of biodiesel derived raw glycerol to value added products. Renew Sustain Energy Rev. 2015;41:113–27.

Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications – a comprehensive review. Adv Drug Deliv Rev. 2016;107:367–92.

Saini P, Arora M, Kumar MNVR. Poly(lactic acid) blends in biomedical applications. Adv Drug Deliv Rev. 2016;107:47–59.

Komanoya T, Suzuki A, Nakajima K, Kitano M, Kamata K, Hara M. A combined catalyst of Pt nanoparticles and TiO₂ with water-tolerant Lewis acid sites for one-pot conversion of glycerol to lactic acid. ChemCatChem. 2016;8:1094–9.

Yin H, Yin H, Wang A, Shen L. Catalytic conversion of glycerol to lactic acid over graphite-supported nickel nanoparticles and reaction kinetics. J Ind Eng Chem. 2018;30:1802091.

Yin H, Zhang C, Yin H, Gao D, Shen L, Wang A. Hydrothermal conversion of glycerol to lactic acid catalyzed by Cu/hydroxyapatite, Cu/MgO, and Cu/ZrO₂ and reaction kinetics. Chem Eng J. 2016;288:332–43.

Moreira ABF, Bruno AM, Souza MMVM, Manfro RL. Continuous production of lactic acid from glycerol in alkaline medium using supported copper catalysts. Fuel Process Technol. 2016;144:170–80.

Arcanjo MRA, Silva J, Rodríguez-Castellón E, Infantes-Molina A, Vieira RS. Conversion of glycerol into lactic acid using Pd or Pt supported on carbon as catalyst. Catal Today. 2017;279:317–26.

Zhang C, Wang T, Liu X, Ding Y. Selective oxidation of glycerol to lactic acid over activated carbon supported Pt catalyst in alkaline solution. Cuihua Xuebao Chinese J Catal. 2016;37:502–9.

Yang GY, Ke YH, Ren HF, Liu CL, Yang RZ, Dong WS. The conversion of glycerol to lactic acid catalyzed by ZrO₂-supported CuO catalysts. Chem Eng J. 2016;283:759–67.

Rodrígues AKO, Maia DLH, Fernandes FAN. Production of lactic acid from glycerol by applying an alkaline hydrothermal process using homogeneous catalysts and high glycerol concentration. Braz J Chem Eng. 2015;32:749–55.

Saleh SNM, Abdullah AZ. Zirconium–cerium oxides supported on SBA-15 as catalyst for shape-selective synthesis of
lactic acid from glycerol. Waste Biomass Valoriz. 2020;12:2565–78.

[65] Sever B, Yıldız M. Conversion of glycerol to lactic acid over Au/bentonite catalysts in alkaline solution. React Kinet Mech Catal. 2020 Aug 1;130(2):863–74.

[66] Xiu Z, Wang H, Cai C, Li C, Yan L, Wang C, et al. Ultrafast glycerol conversion to lactic acid over magnetically recoverable Ni–NiOx/C catalysts. Ind Eng Chem Res. 2020 May 27;59(21):9912–25.

[67] Bharath G, Ramabau K, Hai A, Taher H, Banat F. Development of Au and 1D Ramayapaptite nanohybrids supported on 2D boron nitride sheets as highly efficient catalysts for dehydrogenating glycerol to lactic acid. ACS Sustain Chem Eng. 2020 May 18;8(19):7278–89.

[68] Åkerberg C, Hofvendahl K, Zacchi G, Hahn Åkerberg C, Hofvendahl K, Zacchi G, Hahn-Hägerdal B. Modelling the influence of pH, temperature, glucose and lactic acid concentrations on the kinetics of lactic acid production by Lactococcus lactis ssp. Lactis ATCC 19435 in whole-wheat flour. Appl Microbiol Biotechnol. 1998;49:682–90.

[69] Mel M, Karim MIA, Jamal P, Salleh MR, Zakaria RA. The influence of process parameters on lactic acid fermentation in laboratory scale fermenter. J Appl Sci. 2006;6(10): 2287–91.

[70] Magala M, Kojadinova Z, Karovícová J, Greifova M, Hojerova J. Application of lactic acid bacteria for production of fermented beverages based on rice flour. Food Technol Econ Phys Prop. 2015;33(5):458–63.

[71] Cubas-Cano E, González-Fernández C, Ballesteros M, Tomás-Pejo E. Biotechnological advances in lactic acid production by lactic acid bacteria: lignocellulose as novel substrate. Biofuel Bioprod Biorefin. 2018;12:290–303. doi: 10.1002/bbb.

[72] Breton-Toral A, Trejo Estrada SR, McDonald AG. Lactic acid production from potato peel waste, spent coffee grounds and almond shells with undefined mixed cultures isolated from coffee mucilage from coatepec Mexico. Ferment Technol. 2017;6(1):139. doi: 10.4172/2167-7972.1000139.

[73] Vaidya AN, Pandey RA, Mudilari S, Kumar MS, Chakrabarti T, Devotta S. Production and recovery of lactic acid from polylactide – an overview. Crit Rev Env Sci Technol. 2005;35:429–67. doi: 10.1080/10643380590616818.

[74] Wang Y, Tashiro Y, Sonomoto K. Fermentative production of lactic acid from renewable materials: Recent achievements, prospect and limits. Soc Biotechnol. 2014;119:10–8. doi: 10.1016/j.jbiosc.2014.06.003.

[75] Bron PA, Keereezem M. Engineering lactic acid bacteria for increased industrial functionality. Bioeng Bugs. 2011;2:80–7.

[76] Lu ZH, He F, Shi Y, Lu MB, Yu LJ. Fermentative production of L-(p)-lactic acid using hydrolysed acorn starch, persimmon juice and wheat bran hydrolysate as nutrients. Bioreourc Technol. 2010;101:3642–8.

[77] Wee YJ, Yun JS, Park DH, Ryu HW. Biotechnological production of L-(p)-lactic acid from wood hydrolystate by batch fermentation of Enterococcus faecalis. Biotechnol Lett. 2004;26:71–4.

[78] Givry S, Prevot V, Duchiron F. Lactic acid production from hemicellulose hydrolystate by cells of Lactobacillus bifermantans immobilized in Caalginate using response methodology. World J Microbiol Biotechnol. 2008;24:745–52.

[79] Hétényi K, Németh Á, Sevella B. Investigation and modeling of lactic acid fermentation on wheat starch via SSF, CHF and SHF technology. Per Pol Chem Eng. 2011;55:11–6.

[80] John RP, Namoothiri KM, Pandey A. Simultaneous saccharification and fermentation of cassava bagasse for L-(p)-lactic acid production using Lactobacilli. Appl Biochem Biotechnol. 2006;134:263–72.

[81] Ge XY, Qian H, Zhang WG. Enhancement of L-lactic acid production in Lactobacillus casei from Jerusalem artichoke tubers by kinetic optimization and citrate metabolism. J Microbiol Biotechnol. 2010;20:101–9.

[82] Li Z, Ding SF, Li ZP, Tan TW. L-lactic acid production by Lactobacillus casei fermentation with corn steep liquor-supplemented acid-hydrolysate of soybean meal. Biotechnol J. 2006;1:1453–8.

[83] Wee Y-J, Kim J-N, Ryu HW. Biotechnological production of Lactic Acid and Its recent applications. Food Technol Biotechnol. 2006;44(2):163–72.

[84] Shen XL, Xia LM. Lactic acid production from cellulose material by synergetic hydrolysis and fermentation. Appl Biochem Biotechnol. 2006;133:251–62.

[85] Dumbrepatil A, Adsul M, Chaudhari S, Khire J, Gokhale D. Utilization of molasses sugar for lactic acid production by lactobacillus delbrueckii subsp. delbrueckii mutant Utc-3 in batch fermentation. Appl Environ Microbiol. 2008;74:333–5.

[86] Wang L, Zhao B, Liu B, Yu B, Ma C, Su F, et al. Efficient production of L-lactic acid from corncob molasses, a waste by-product in xyitol production, by a newly isolated xylose utilizing Bacillus sp. strain. Bioresour Technol. 2010;101:7908–15.

[87] Shibata K, Flores DM, Kobayashi G, Sonomoto K. Direct L-lactic acid fermentation with sago starch by a novel amylolytic lactic acid bacterium, enterococcus faecium. Enzyme Microb Technol. 2007;41:149–55.

[88] Senedese AL, Maciel Filho R, Maciel MR. L-lactic acid production by lactobacillus rhamnosus ATCC 10863. Sci World J. 2015;2015:501029. doi: 10.1155/2015/501029.

[89] Hauly MCO, Oliveira AR, Oliveira AS. Lactic acid production by L. curvatus in sugarcane molasses. Semina: Ciências Agrárias; 2003, Vol. 24, p. 133–42.

[90] Hofvendahl K, Hahn-Hägerdal B. Factors affecting the fermentative lactic acid production from renewable resources. Enzyme Microb Technol. 2000;26(2–4):87–107.

[91] Yoo I-KK, Chang H-N, Lee E-G, Chang Y-K, Moon S-H. Effect of pH on the production of lactic acid and secondary products in batch cultures of Lactobacillus casei. J Microbiol Biotechnol. 1996;6(6):482–6.

[92] John RP, Namoothiri KM, Pandey A. Fermentative production of lactic acid from biomass: an overview on process developments and future perspectives. Appl Microbiol Biotechnol. 2007;74(3):524–34.

[93] Nikkila KK, Hujanen M, Leisola M, Palva A. Metabolic engineering of Lactobacillus helveticus CNRZ32 for production of pure L-(+)-lactic acid. Appl Environ Microbiol. 2000;66:3835–41.

[94] Hideo K, Kazutami I. 3. Studies on lactic acid fermentation. J Agric Chem Soc Jpn. 1955;19(1):15–21. doi: 10.1080/03758397.1955.10857258.
[95] Shi L, Weiping D, Yanyun L, Qinghong Z, Ye W. Catalytic conversion of cellulose-based biomass and glycerol to lactic acid. J Energy Chem. 2018;24:10460–67. doi: 10.1016/j.jchem.2018.07.012.

[96] Adhavan A, Takahashi K, Chong SS, Jurgen-Lohmann DL, Osabe M. Patent: WO 2013/146557 Al. 2013.

[97] Cubas-Cubano E, González-Fernández C, Ballestros M, Tomás-Pejo E. Review: lactic acid production by lactic acid bacteria. Biofuel Bioprod Biorefin. 2018. doi: 10.1002/bbb.

[98] Mazumdar S, Clomburg JM, Gonzalez R. Escherichia coli strains engineered for homofermentative production of α-lactic acid from glycerol. App Env Microbiol. 2010;76(13):4327–36.

[99] Zavrazhnov SA, Esipovich AL, Danov SM, Zlobin SY, Belousov AS. Catalytic conversion of glycerol to lactic acid: state of the art and prospects. Kinetics Catal. 2018;59(4):459–71.

[100] Gruber PR. Cargill Dow LLC. J Ind Ecol. 2004;7(3–4):209–13.

[101] Guyot JP, Calderon M, Morlon-Guyot J. Effect of pH control on lactic acid fermentation of starch by lactobacillus manihotivorans LMG 18010\(^{\dagger}\). J Appl Microbiol. 2000;88:176–82.

[102] Malee W, Pisutpaisal N, Boonyawanich S. Impact of glycerol concentration on lactic acid fermentation. Adv Mater Res. 2013;610:613:356–8.

[103] Lin HTW, Huang MY, Kao TY, Lu WJ, Lin HJ, Pan CL. Production of lactic acid from seaweed hydrolysates via lactic acid bacteria fermentation. Fermentation. 2020;6:37.

[104] Narayanan N, Roychoudhury PK, Srivastava A. L(+) lactic acid fermentation and its product polymerization. Electron J Biotechnol. 2004;7(2):167–79.

[105] Prada-Palomo Y, Romero-Vanegas M, Díaz-Ruíz P, Molina-Velasco D, Guzmán-Luna C. Lactic acid production by Lactobacillus sp. from biodiesel derived raw glycerol. Tecnol Futuro. 2012;5(1):57–66.

[106] Aragón DM, Rosas JE, Martínez F. Lactic acid properties, applications and production: a review. Trends Food Sci Technol. 2013;30:218–24.

[107] Li Y, Cui F. Microbial laactic acid production from renewable resources. Sustain Biotechnol. 2010;6(10):211–28.

[108] Xiao L, Wang B, Yang G, Gauthier M. Poly(lactic acid)-based biomaterials: synthesis, modification and applications. Biomed Sci Eng Technol. 2012;5(1):57–65.

[109] Hastati DY, Hambali E, Syamsu K, Warsiki E. Potential lactic acid production from crude glycerol as the precursor of polylactic acid analog: literature review. International Conference on Biomass: Technology, Application, and Sustainable Development; 2017. p. 65.

[110] Vaidya AN, Pandey RA, Mudliar S, Suresh Kumar M, Chakrabarti T, Devotta S. Production and recovery of lactic acid for polylactide – an overview. Crit Rev Environ Sci Technol. 2005;35(5):429–67. doi: 10.1080/10643380590966181.

[111] https://www.dlahandlu.pl/detal-hurt/wiadomosci/grupa-orlen-wdraza-nowa-biotechnologie-dla-przemyslu-spozywczego,89186.html [access: 02-02-2021].

[112] https://www.dlahandlu.pl/detal-hurt/wiadomosci/grupa-orlen-wdraza-nowa-biotechnologie-dla-przemyslu-spozywczego,89186.html [access: 02-02-2021].

[113] https://naukawpolsce.pap.pl/aktualnosci/news%2C370213%2Cekologiczne-poliestry-z-kwasu-mlekowego. html [access: 02-02-2021].

[114] https://bioenergyinternational.com/biochemicals-materials/praj-lygos-partner-co-develop-advanced-lactic-acid-yeast-technology-bio-based-products [access: 02-02-2021].

[115] https://trendeconomy.com/data/commodity_h2/1520 [access: 02-02-2021].

[116] https://trendeconomy.com/data/h2/Poland/1703 [access: 02-02-2021].

[117] https://www.money.pl/gielda/pkn-orlen-wybuduje-w-trzebini-instalacje-kwasu-mlekowego-za-10-mln-zl-6527371609131138a.html [access: 07-006-2021].