PRIMJENA INTEGRIRANIH TEHNOLOGIJA ZA SMANJENJE OTPADA, UŠTEDU ENERGIJE I SMANJENJE EMISIJE STAKLENIČKIH PLINOVA U POLJOPRIVREDNO-PREHRAMBENOM SEKTORU

APPLICATION OF INTEGRATED TECHNOLOGIES FOR WASTE MINIMIZATION, ENERGY SAVING AND GREENHOUSE GASES EMISSION REDUCTION IN AGRO-FOOD SECTOR

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Sažetak: *Sadašnje gospodarenje otpadom iz poljoprivredno-prehrambenog sektora u Hrvatskoj predstavlja specifičan problem za okoliš zbog neodgovarajućeg i nekontroliranog gospodarenja velikim dijelom tog otpada, što može uzrokovati onečišćenje zraka, tla, površinskih i podzemnih voda.*

Primjena integriranih tehnologija u poljoprivredno-prehrambenom sektoru ima veliki potencijal u smislu smanjenja otpada, uštede energije i smanjenja emisije stakleničkih plinova. Razvojem procesa teži se nultim emisijama otpada. Poljoprivredno-prehrambeni otpad može se koristiti za proizvodnju biogoriva pomoću različitih procesa fermentacije. Optimizacija integriranog procesnog sustava vodi efikasnijem korištenju sirovina i otpada, u svrhu ostvarivanja održivog procesa.

Ciljevi EU, 20% energije proizvedene iz obnovljivih izvora i 20% smanjenja emisije stakleničkih plinova do 2020., mogu se ispuniti primjenom novih, ekološki prihvatljivih tehnologija za proizvodnju energije i obradu otpada uz manje troškove, u pogledu potrošnje energije i utjecaja na okoliš.
Ključne riječi: *Poljoprivredno-prehrambeni otpad, energija, emisija stakleničkih plinova*

Abstract: *Current management of agro-food waste in Croatia represents a specific environmental problem due to inadequate and uncontrolled management practices of a large portion of this waste stream which can lead to pollution of air, soil, surface and ground water.*

Application of integrated technologies in agro-food sector has significant potential in terms of waste minimization, energy saving and greenhouse gases (GHGs) emission reduction. Processes development tends to zero emissions of waste. Agro-food waste can be used for production of biofuel through various fermentation processes. Optimization of integrated process systems leads to more effective utilization of resources and waste in order to accomplish sustainable process.

The EU targets, 20% of energy generation from renewable sources and 20% reduction of GHG emissions by 2020, can be fulfilled by the implementation of new environmentally-friendly technologies to produce energy and treat waste in a less costly way, in terms of energy consumption and environmental impact.
Keywords: *Agro-food waste, energy, GHG emission*

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1. INTRODUCTION

The main reasons for the spread of renewable energy sources are to increase the security of the energy supply in order to achieve energy independence. The dependence on fossil fuels as primary energy source has led to global climate change, environmental degradation, and human health problems (Aragaw et al., 2013). The accumulation of organic waste is thought to be reaching critical levels in almost all regions of the world. These organic wastes require to be managed in a sustainable way to avoid depletion of natural resources, minimize risk to human health, reduce environmental burdens and maintain an overall balance in the ecosystem (Khalid et al., 2011). Producing and utilizing renewable energy, both in a global and a national context, is necessitated by the synergistic effect of climate change and the long term, continuous price rise of fossil fuels (Meggyes et al., 2012). Bio-energy related processes convert the energy value of various biomass residuals to socially useful energy. Biomass residuals come from agricultural, animal, and a variety of industrial operations, as well as from human wastes.

Furthermore, the wastes often cause serious environmental harm, and their collection and conversion to energy would provide a giant benefit to environmental quality (Rittmann, 2008).

The management of agro-food waste has posed a serious economic and environmental concern. Recently, anaerobic digestion (AD) of agro-food wastes has attracted more interest because of current environmental problems, most especially those concerned with global warming (Nasir el al., 2012). Bioconversion of agro-food waste to energy in terms of ethanol, hydrogen (H_2), methane (CH_4) and biodiesel is economically viable. In addition to biogas, a nutrient-rich digestate produced can also be used as fertilizer or soil conditioner (Kiran et al., 2014). Due to increasing needs for renewable energy generation and diversion of organic residuals from landfills to reduce the GHG emissions and other environmental impacts, treatment of agro-food waste using AD technologies has become a more attractive method for agro-food waste management (Chen et al., 2010). The choice of method must always be based on maximum safety, minimum environmental impact, and as far as possible, on valorisation of the waste and final recycling of the end products (Ahring, 2003).

The production of biogas, particularly CH_4 via anaerobic processes, is an acceptable solution for waste management because of its low cost, low environmental impact, low production of residual sludge and its utilization as a renewable energy source (Ahring B, 2003; Angelidaki et al., 2011; Morita et al., 2012). The AD is a chain of interconnected biological reactions, where the organic matter (in the form of carbohydrates, proteins, lipids or more complex compounds), is transformed into CH_4, carbon dioxide (CO_2), and anaerobic biomass, in an oxygen-free environment. This biological process is used to simultaneously treat waste and wastewater and to produce biogas (Donoso-Bravo et al., 2011). Different types of agro-food waste result in varying degrees of CH_4 yields, and thus the effects of mixing various types of agro-food waste and their proportions should be determined on a case by case basis (Chen et al., 2010). AD technologies show great adaptability to a broad spectrum of different input materials (Kwietniewska et al., 2014). AD of single substrates (mono-digestion) presents some drawbacks linked to substrate properties. For instance, (i) sewage sludge (SS) is characterized by low organic loads; (ii) animal manures (AM) have low organic loads and high nitrogen (N) concentrations, that may inhibit methanogens; (iii) the organic fraction of municipal solid waste (OFMSW) has improper materials as well as a relatively high concentration of heavy metals; (iv) crops and agro-industrial wastes are seasonal substrates, which might lack N; (v) slaughterhouse wastes (SHW) include risks associated with the high concentration of N and/or long chain fatty acids (LCFA), both potential inhibitors of the methanogenic activity; and (vi) food waste (FW) contains easily biodegradable macromolecular organic matter, but also contains various trace elements (Mata-Alvarez et al., 2014; Zhang et al., 2011). Most of these problems can be solved by the addition of a co-substrate in what has been recently called anaerobic co-digestion (AcoD).

The improvement in CH_4 production is mainly a result of the increase in organic loading rate (OLR). It is important to choose the best co-substrate and blend ration in order to: (i) favour positive interactions, i.e. synergisms, macro- and micro-nutrient equilibrium and moisture balance; (ii) dilute inhibitory or toxic compounds; (iii) optimise CH_4 production, and (iv) enhance digestate stability (Mata-Alvarez et al.,2011; Astals et al., 2014). Pretreatment techniques are used to enhance the AD of organic solid waste, including mechanical, thermal, chemical and biological methods (Ariunbaatar et al., 2014). Solid-state anaerobic digestion (SS-AD) generally occurs at solid concentrations higher than 15%. In contrast, liquid anaerobic digestion (AD) handles feedstocks with solid concentrations between 0.5% and 15%. AM, SS, and FW are generally treated by liquid AD, while OFMSW and lignocellulosic biomass such as crop residues and energy crops can be processed through SS-AD (Li et al., 2011).

With conservation and efficiency in effect, renewable substitutes for fossil fuels will have a chance to slow or reverse global warming, but only if they can be implemented on a very large scale which must be considered when evaluating the value of any renewable-energy scheme (Rittmann, 2008). There are multiple characteristics that make this technology applicable to industrial energy generation processes. Nevertheless, improvements in both environmental characteristics and overall process economics are still required to make the technology acceptable broad base. An important economic consideration is the fact that the biogas can be produced at the biomass production site reducing transportation costs. The AD plants can be scaled down that makes the process ideal for rural area development (Molino et al., 2013).

Pursuant to Directive 2009/28/EC on the promotion of the use of energy from renewable sources (RES), Croatia has undertaken to increase the use of renewable energy - the mandatory 20% share of RES in gross final energy consumption in the European Community must be achieved by 2020. To fulfil this primary objective, Croatia has adopted National Renewable Energy Action Plan by 2020 (NREAP) on 17 October 2013 (Ministry of Economy, 2013). The NREAP determines the overall national target for renewable energy to the prescribed methodology and sectoral targets and trajectories in the production of electricity consumption for heating and cooling and transport energy from RES. The NREAP determines the existing and planned policy for RES as instruments, measures and mechanisms in order to achieve the goals by 2020. Biogas from wastes is a versatile renewable energy source, which can be used for replacement of fossil fuels in power and heat production, and it can be used also as gaseous vehicle fuel. Methane-rich biogas (biomethane) can replace natural gas as a feedstock for producing chemicals and materials or simply be injected into the gas grid. It can significantly reduce GHG emissions compared to fossil fuels (Liebetrau et al., 2013; Rehl et al., 2013; Scholz et al., 2011; Weiland, 2010).

2. METHODOLOGY

2.1. Waste minimization in agro-food sector

The transposition of the Acquis in the area of waste management into the Croatian legislation has been completed. Waste Framework Directive 2008/98/EC is transposed by the Sustainable Waste Management Act (Official Gazette No. 94/13). Management of the different types of waste is harmonised by objectives of the waste hierarchy. The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal.

In the agro-food industry zero-point discharge is desired. In general there are three types of strategies: (i) end of pipe abatement, (ii) reduction at source, and (iii) zero-point discharge. Application of integrated technology in agro-food sector enhances the safety and quality of the product as well as reducing the energy requirements and environmental impact. Integrated technologies such as high-rate anaerobic reactors (Guardia-Puebla et al., 2014) and membrane technology allow recovery and re use of by product and wastes as raw material. Using different membrane processes separated substances are often recoverable in a chemically unchanged form and are therefore easily re-used.

2.2. Anaerobic digestion of agro-food waste

The AD is a process by which almost any organic waste can be biologically transformed into another form, in the absence of oxygen. The diverse microbial populations degrade organic waste, which results in the production of biogas and other energy-rich organic compounds as end products.

A series of metabolic reactions such as hydrolysis, acidogenesis, acetogenesis and methanogenesis are involved in the process of anaerobic decomposition (Mata-Alvarez et al., 2014; Molino et al., 2013; Appels et al., 2011) as shown in Fig.1.

The biodegradation process begins with the first phase in which high molecular materials and granular organic substrates (e.g., lipids, carbohydrates, protein) are hydrolysed by fermentative bacteria into small molecular materials and soluble organic substrates (e.g., fatty acids, glucose, amino acids). During the AD of complex organic matter the hydrolysis is the first and often rate-limiting step (Angelidaki et al., 2014) because the hydrolytic enzyme should be primarily adsorbed on the surface of solid substrates (Coelho et al., 2011). Secondly, small molecular materials and granular organic substrates are degraded into volatile fatty acids (VFA) (e.g., acetate, propionate and butyrate) along with the generation of by-products. Thirdly, the organic substrates produced in the second step are further digested into acetate, H_2, CO_2 which could be used by methanogens for CH_4 production (Zhang et al., 2014). Feedstock characteristics and process configuration are the main factors affecting the performance of AD (Molino et al., 2013).

2.2.1. Characteristic of agro-food waste

The physical and chemical characteristics of the agro-food waste affect the biogas production and process stability (Kiran et al., 2014). Substrate mixture should be appropriately regulated for optimal operation as to carbon/nitrogen (C/N) ratio, moisture, pH, concentrations of nutrients, inhibitors, toxic compounds, biodegradable organic matter, dry matter, and other factors (Mata-Alvarez et al., 2011). The AcoD is preferably used for improving yields of AD of organic wastes. Co-digestion of mixtures stabilizes the feed to the bioreactor, thereby improving the C/N ratio and decreasing the concentration of nitrogen (Cuetos et al., 2008). The use of a co-substrate with a low nitrogen and lipid content waste increases the production of biogas due to complementary characteristics of both types of waste, thus reducing problems associated with the accumulation of intermediate volatile compounds and high ammonia concentrations (Castillo et al., 2006). Mixtures of agricultural, municipal and industrial wastes can be digested successfully and efficiently together (Table 1.).

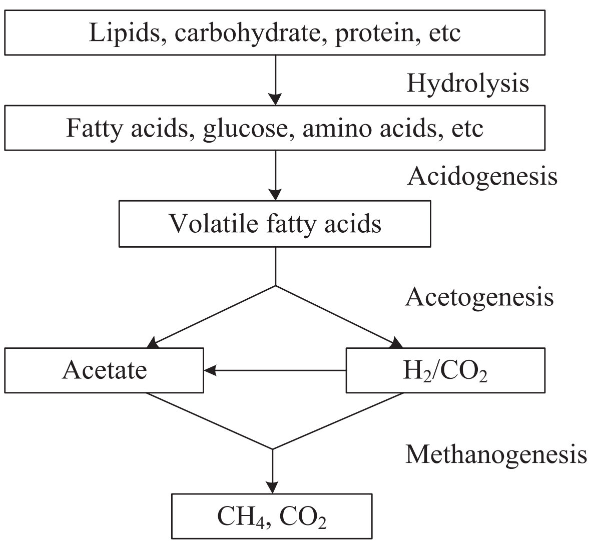

Figure 1. Four steps in the AD of organic substrate (Mata-Alvarez et al., 2014)

Table 1. Relative biogas production rates and CH_4 yield from co-digestion of agro-food organic waste (Khalid et al., 2011)

Substrate	Co-substrate	Biogas production rate (l/d)	CH_4 yield (l/kg VS*)	Comments
Cattle excreta	Olive mill waste	1.10	179	The co-digestion system produced 337% higher biogas than that of excreta alone.
Cattle manure	Agricultural waste and energy crops	2.70	620	Significant increase in biogas production from the co-digestion was observed.
Fruit and vegetable waste	Abattoir wastewater	2.53	611	The addition of abattoir wastewater to the feedstock increased biogas yield up to 51.5%.
Pig manure	Fish and bio-diesel waste	16.4	620	Highest biogas production rate was obtained by a mixture of wastes.
Potato waste	Sugar beet waste	1.63	680	Co-digestion improved CH_4 yield up to 62% compared to the digestion of potato waste alone.
Primary sludge	Fruit and vegetable waste	4.40	600	Co-digestion produced more biogas as compared to primary sludge alone.
Slaughterhouse waste	Municipal solid waste	8.60	500	Biogas yield of the co-digestion systems doubled that of the slaughter house waste digestion system.

2.2.2. Anaerobic bioreactor configurations

According to Ward and his co-workers, an anaerobic bioreactor should be designed in a way that allows a continuously high and sustainable OLR with a short hydraulic retention time (HRT) and has the ability to produce the maximum level of CH_4 (Ward et al., 2008). Several types of bioreactors are currently in use but the three major groups of bioreactors commonly in use include batch reactors, a one stage continuously fed system and a two stage or multi-stage continuously fed system (Khalid et al., 2011). Batch reactors are the simplest, filled with the feedstock and left for a period that can be considered to be the HRT, after which they are emptied. The second type of bioreactors is known as 'one-stage continuously fed systems', where all the biochemical reactions take place in one bioreactor. The third type of bioreactors are 'two-stage' or 'multi-stage continuously fed systems', in which various biochemical processes such as hydrolysis, acidification, acetogenesis and methanogenesis take place separately (Ward et al., 2008). The two-stage system is considered a promising process to treat organic wastes with high efficiency in term of degradation yield and biogas production (Fezzani et al., 2010; Zuo et al., 2014). Currently, most of anaerobic digesters are single-stage systems, which e.g. accounts for 95% of the European full-scale plants (Nagao et al., 2012).

AD of FW is a complex process that should simultaneously digest all organic substrates (e.g., carbohydrate and protein) in a single-stage system. It is governed by different key parameters such as temperature, VFA, pH, ammonia, nutrients, trace elements, and others. A good nutrient and trace element balance, and a stable environment are required for microbial growth. It is therefore extremely important to maintain the key parameters within the appropriate range for long term operation of AD (Zhang et al., 2014; Naik et al., 2014).

Integrated processes for the sustainable treatment of livestock waste consist of AD for biogas production, and different type of reactors for the treatment of the liquid stream produced from the AD. Integrated technology for the sustainable treatment of livestock waste such as sequencing batch reactor (SBR) and membrane bioreactor (MBR) can be applied for treatment of liquid stream from AD.

3. DISCUSSION

3.1. Techno-economic and ecological aspects of biogas production from agro-food waste

Energy recovery from biogas has taken a leap forward in the European Union. The electricity generation from biogas in 2012, with the growth rate of 22.2% reached 46.3 TWh, and 64.9% of this was from cogeneration plants (EUROBSERV'ER, 2013). Germany is Europe's biggest biogas producer and the market leader in biogas technology. The primary biogas energy output reached 6.4 Mtoe in 2012, which was essentially picked up by electricity generation which rose 28.6% year-on-year to reach 27.2 TWh by the end of 2012. In 2013, the number of biogas plants reached 9,200, including 107 units producing biomethane (AEBIOM, 2012; GreenGasGreeds, 2013).

In Croatia, eleven biogas plants for agro-industrial wastes with a total installed power of 11.135 MW are connected to the power grid, within the system of eligible power producers. Additionally, another nine biogas plants, with total installed power of 7.544 MW, have signed power purchase agreements with the Croatian Energy Market Operator (HROTE). The Croatian Tariff System makes the size of the biogas plant of ≤ 300 kW advantageous for investors.

According to the results of laboratory batch-tests based on the work of Hublin and her co-workers (Hublin et al., 2012; Hublin et al., 2013), parameters of the full-scale biogas plant designed to process manure and whey from dairy cows on Croatian farms have been estimated. The economic viability of a medium-scale biogas power plant has been investigated and a full-scale biogas power plant has been modelled (Hublin et al., 2014). Using the manure and whey from 450 cows to feed the digester, it is estimated that 686,830 m^3 of CH_4 could be produced each year, capable of generating a maximum 2,160,000 kWh of electricity and 2,448,000 kWh of heat. It is assumed that the electricity produced would be fed into the national grid system and the price paid would be the subsidised tariff from the Croatian Tariff System for Electricity Production from Renewable Energy Sources for 14 years, with market prices applying thereafter. Some of the generated heat would be used to heat the digester and the rest sold to nearby greenhouses and the residue spread on farmland. Plant would be profitable in the twelfth and fifteenth year. CO_2 emissions would be reduced, by approximately 1.7 kilotonnes a year for each kWh of electricity produced and by 1.8 kilotonnes a year for each kWh of heat generated. This renewable energy is assumed to replace electricity and heat generated from coal-fired power plants. CH_4 reductions of 5.7 kilotonnes CO_2-equivalents (the amount of CO_2 which would have the same global warming impact) a year could also be achieved by preventing farm waste CH_4 emissions from entering the atmosphere. In addition to producing RES, this method could avoid pollution of water from manure and whey entering rivers and streams.

A pilot-scale AcoD research study by Liu and his co-workers (Liu et al., 2012) elucidate the feasibility of AD as an effective disposal method for municipal biomass waste (MBW), focusing on biogas production and GHG reduction. FW, fruit vegetable waste (FVW), and dewatered SS were co-digested in a continuous stirred-tank reactor (CSTR) for biogas production. Stable operation was achieved with a high biogas production rate. Compared with the landfill baseline, it is concluded that GHG reduction is an important environmental benefit from MBW digestion. Therefore, AcoD is assumed as a promising alternative solution for MBW because it contributes significantly to the sound management of municipal solid waste.

4. CONCLUSION

The AcoD of agro-food waste gives the possibility of treating different kind of organic waste more efficient, increasing specific CH_4 yields. AD technology can solve two complex problems. On one side it is efficient conversion from biodegradable organic waste to electricity production; on the other it allows efficient wastes treatment.

Advantages of AcoD of biodegradable agro-food waste regarding the profitability of the plant and the convenience in realising an AD plant to produce biogas is enabled by the benefits from the sale of electric energy at favourable prices.

Positive ecological effects could be obtained by using biogas. Direct reduction of CO_2 emissions could be achieved by using biogas as fuel, which encourages rational energy consumption and energy savings. Indirect reduction of CH_4 emissions could be accomplished by reducing the amount of landfilled waste.

5. LIST OF ABBREVIATIONS AND SYMBOLS

AcoD	- anaerobic co-digestion
AD	- anaerobic digestion
AM	- animal manure
CH_4	- methane
C/N	- carbon/nitrogen ratio
CO_2	- carbon dioxide
CSTR	- continuous stirred-tank reactor
FVW	- fruit vegetable waste
FW	- food waste
GHG	- greenhouse gas
H2	- hydrogen
HROTE	- Croatian Energy Market Operator
HRT	- hydraulic retention time
LCFA	- long chain fatty acids
MBR	- membrane bioreactor
MBW	- municipal biomass waste
N	- nitrogen
NREAP	- National Renewable Energy Action Plan
OFMSW	- organic fraction of municipal solid waste
OLR	- organic loading rate
RES	- renewable source
SBR	- sequencing batch reactor
SHW	- slaughterhouse waste
SS-AD	- solid-state anaerobic digestion
VFA	- volatile fatty acids

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