A Circular Economy Approach for Sustainable Economic Development

Dinda, Soumyananda

Department of Economics, University of Burdwan, India

May 2020

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Soumyananda Dinda[Ψ]

Department of Economics, University of Burdwan, India

Revised Version: May 29, 2020

Abstract

This paper focuses on the circular economy approach which is based on the principle of *recycle of resources*. It is an alternative to the existing linear economy that is based on the principle of '*take-make-dispose*', which is unsustainable for economic growth due to limitation of resources in the world. This study especially set up a circular economy model for sustainable development in the frame work of endogenous economic growth incorporating waste as valuable stock for further production. The paper highlights (a) stock of waste accumulation, (b) dynamics of waste in closed-loop system, and (c) economic growth path. Recycling economic activities contributes in the economic development with reuse of resources without degrading environment. This paper tangentially provides empirical support to our model for sustainable development.

***Key* Words**: Circular Economy, Close-loop system, Economic Growth, Linear Economy, Recycle of Waste, Sustainable Development, Take-Make-Dispose, Waste.

JEL *Classification Number*: Q_{53}, O_{44}, P_{28},

Biographical notes:
Soumyananda Dinda teaches at the Department of Economics, Burdwan University. Previously he taught at SKBU, Purulia; CIMP; Madras School of Economics; University of Bath, UK; SRFC, Beldanga; also taught as a Guest Lecturer in Presidency College, & University of Calcutta. He was a Research Fellow at Indian Statistical Institute since 1997. He is working on green economics, climate change and social aspects. He has papers on *Ecological Economics*, *Economics and Human Biology*, *Journal of Socio-Economics*, *International Journal of Global Environmental Issues*, *International Trade Journal*, *International Journal of Social Economics*, *International Journal of Green Economy, Journal of Public Economic Theory*, etc.

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[Ψ]Address for Correspondence: Department of Economics, Old Humanities Building, Golapbag Campus, University of Burdwan, Burdwan -713104, East Burdwan, West Bengal, India. Email: sdinda2000@yahoo.co.in , and sdinda@eco.buruniv.ac.in

1. Introduction

This paper investigates circular economy approach for sustainable development in the framework of endogenous economic growth model. This study attempts to ensure the achievable sustainable development goals (SDG) for 2030 focusing on the circular economy approach incorporating waste as valuable stock for further production. Recycling activities contribute in economic growth and development with reuse of resources without degrading environment (Anderson 2007, George et al. 2015, Webster 2015). Environmental quality starts to degrade with rapid industrialization especially after the Second World War (Bovenberg and Smulders 1995). Industrialisation adopts the linear economy model based on the principle of '*take- make- dispose*'; and it generates huge amount of waste along with rapid economic growth[1]. This open- looped linear economy creates pressure on extraction of natural resources and waste disposal into nature. Ultimately economic developmental activities become unsustainable. So, question arises how economic activities restore sustainability. Is there any alternative development mechanism for sustainable economic growth?

One possible solution is to adopt recycling resources. This economic system internalizes environmental externalities in terms of waste and pollution stock. Traditional economic growth theories (Solow 1956, Romer 1986, and Lucas 1988 etc.) and other earlier studies (Beckerman 1992, Nordhus 1974, Solow 1974, World Bank 1992) ignore a relevant dynamics of accumulation of waste resources, which may trigger to move towards sustainable development. Recently, development economists and other social scientists introduce the concept of circular economy model (Ellen MacAthur foundation 2013, 2015, 2016; Andersen 2007; Geng et al. 2012; George et al. 2015; Yuan, Bi and Moriguichi 2006). In this context, this paper focuses on the circular economy and set up a model following the principle of *recycle of resources* which convert wastes to productive resources. In this circular economy model, waste becomes a value producing resources (McDonough et al. 2003), and waste[2] resource might turn to be one contributing factor of economic growth in a restrictive model (George et al. 2015).

[1] Rising economic growth increases industrial demand for resources which are limited in this planet (Club of Rome; see Meadows et al. 1972 and also see Stokey 1998).

[2] Value of products is important in market, and disposes valueless wastes that damage the environment.

Following George et al. (2015) and Dinda (2014, 2016) this paper aims to incorporate the concept of circular economy in the economic growth theory, and deals with this issue by combining the accumulation of stock of waste and pollution along with physical capital. This paper considers the generation of waste within the economic system, which is different from George et al. (2015) that consider recyclable and polluting resources. Relaxing some restrictions, this paper builds up a model and shows one sustainable economic development path.

The paper is organised as the follows: Section 2 reviews the existing literature in brief including the background history. Section 3 describes the model setup for this study. Section 4 analyses the model and its properties. Section 5 provides empirical support for the model, and finally the paper concludes with remarks.

2 Literature Review

Traditionally economic literature (Solow 1956, Romer 1986, Lucas 1988, Stokey 1998, Aghion and Howitt 1998, etc.) discusses about the economic growth and development mechanics of social wellbeing in a linear economy, which refers to a simple linear process based on the principle of '*take-make-dispose*'. We take, make and dispose materials in the linear economy model which relies on large quantities of cheap, easily accessible materials and energy (Ellen MacAthur foundation 2012, 2013, 2014, 2015). This open- looped linear economy creates pressure on extraction of natural resources and waste disposal into nature. The linear economy is synonymous with industrialization, which has been a driving force of economic growth since the 19th century. Adopting successful industrial strategy several nations become rich and improve their standard of living or/and social welfare. However, rapid industrialization generates huge waste and pollution that destroy natural resources and also degrades environmental quality. Braungart and McDonough (2002) rightly point out that resources are extracted, shaped into products, sold and eventually disposed of in a '*grave*' of some kind, usually landfill.

Industrialization reduces some intrinsic functional capacity of nature and its living system, which allows resources to return to nature through certain cycles and/or flows[3]. Nature accommodates everything including industrial wastes with certain limitations. In this context, concept of the circular economy (CE) emerges from thought of the eco-industrial development theory, which is based on the philosophy of co-existence of healthy economy with healthy environment (Geng and Doberstein, 2008; Park et al., 2010). The circular economy represents a fundamental alternative to the dominant linear economic model based on a '*take- make- consume- through away*' pattern (Reichel, De Schoenmakere and Gillabel 2016). The concept of circular economy is based on balancing healthy environment and economy; and it drives optimal resource efficiency utilizing through the product's life cycle or/and closed loop material flows. The circular economy model aims to solve industrial waste management problems, internalizing the environmental externalities, minimising waste, and moves toward sustainability (World Bank 2012).

The concept of the circular economy approach probably emerges from environment and development economics branch, and others may argue differently. However, recently, Ellen MacAthur foundation (2012, 2013, 2015) and others (Andersen 2007; Geng et al. 2012; George et al. 2015; Korhonen et al. 2018; Heshmati 2018; Yuan, Bi and Moriguichi 2006; McDonough et al. 2003; etc.) popularise it. Actually, the notion of circularity idea is deep rooted in terms of historical origin. Boulding (1966) is the pioneer to motivate for the idea of circular economy in his *spaceship economy*. Boulding (1966) suggests to implement a cyclical ecological system instead of the wasteful linear economic model. He suggests to construct self-replenishing economy incorporating the notion of spiral or close loop. In 1970s, the Club of Rome highlights '*Limits to growth*' focusing on finiteness of the Earth (Meadows, et al. 1972). Daly (1991) points out a sinking boat while Arrows et al. (1995) indicate the carrying capacity of an economy. Anderson (2007) highlights environmental economics of the circular economy[4], while George et al. (2015) analyse environmental quality in a theoretical model with restricted

[3] The circular economy model optimally uses resources over the entire life of a product cycle – from '*take*' stage to *product's end life*. The objective of this circular economy is to take least resources and utilizes fully all products, components and materials through their life cycle.
[4] It should be noted that Pearce and Turner (1989) use the phrase 'Circular Economy' in the early 1990s.

conditions. Stahel (2010) develops the idea of 'performance economy' which may stimulate others to adopt the close loop system in their respective nations.

Recently, several countries (like Australia, China, Finland, Germany, Japan, the Netherlands, Sweden, UK, and other European nations, etc.) have adopted certain development strategies incorporating circular economy model (Yuan et al. 2006, Geng et al. 2012). Following above said literature this study attempts to ensure persistent production and consumption through adoption of *recycle of resources* for sustainable development in the framework of endogenous economic growth model. The paper highlights the stock of waste accumulation and its dynamics in the closed-loop system.

3. Model Setup

Consider a closed matured capitalistic economy where population is fixed or unchanged. For simplicity, consider a single individual who produces and consumes goods. His/her production and consumption activities generate wastes. (S)he uses resources (or, the polluting factors) as input in his/her production process. Pollution is generated (i) for using polluting resources in the production process and (ii) from accumulated wastes.

3.1 Production

The representative firm traditionally produces output, *y*, using composite capital (i.e., manmade capital or combination of physical and human capital), *k,* and resources, R_m, which is the source of all pollutions and wastes generation. Actually, R_m is polluting resource in the production system. A well-defined production function is

$$y = f(k, R_m)\,, \qquad (1)$$

$$f_k > 0,\ ,\ f_{R_m} > 0,\ f_{kk} < 0,\ \ f_{R_m R_m} < 0,\ f_{kR_m} > 0,\ f(k,0) = f(0,R_m) = 0\,.$$

Equation (1) provides a well behaved production function. Both inputs are essential for production of *y* for a given production technology. Traditional output, *y*, is used for consumption and capital accumulation for further production. Pollution and waste are generated (as the by-products) in the production process of y goods. Let pollution, *P*, and waste, W_s, both are the function of output, y. In other words, output, y, is associated with P and W. Consider (for simplicity) composite capital, k, is non-polluting factor of production, and R_m is only polluting factor of production.

Now, more specifically both pollution and waste depend on use of polluting resources, R_m, hence, each unit of pollution is generated from corresponding each unit of output production which is associated with units of resource inputs; so, $p = \gamma(y), \Rightarrow p = \gamma(R_m)$, where $\gamma_{R_m} > 0$, $\gamma_{R_m R_m} \leq 0$ and partly pollution is reduced due to absorption capacity of nature, however, $\gamma_{R_m R_m} \leq 0$ suggests that change of pollution level may have certain cap or threshold level; while waste generating function is $W_S = l(y), \Rightarrow W_S = l(R_m)$, where $l_{\mathrm{R_m}} > 0$ and $l_{\mathrm{R_m R_m}} > 0$ (or $l_{\mathrm{R_m R_m}} < 0$ in case of limited resources). Traditional economy generates waste which accumulates over time and it turns to be a stock. This waste stock grows exponentially, it can be expressed as $l(R_m)$ with $l_{\mathrm{R_m}} > 0$ and $l_{\mathrm{R_m R_m}} > 0$ properties. In this context this waste stock can be converted to productive resource and the circular economy starts to operate to control waste and related problems. Let us try to understand the economic development mechanism of the circular economy.

The Circular Economy

3.2 Recycling Production function

Now, consider the situation where individual produce q product using recyclable waste which reduce the pressure on environment and natural resources. The representative firm produces recyclable output, q, using composite capital, k; polluting resources, R_m, and recyclable waste, RW_S. The recyclable output, q, is potential for both consumable and further recyclable again and again. The recyclable output function is also well-defined as

$$q = h(k, R_m, RW_S)\ , \qquad (2)$$

$h_k > 0,\ h_{RW_S} > 0,\ h_{R_m} > 0,\ h_{kk} < 0,\ h_{RW_S RW_S} < 0,\ h_{R_m R_m} < 0,$

$h(0, R_m, RW_S) = 0$, $h(k, 0, 0) = 0$, $h(k,\ R_m, 0) = 0$, and $h(k, 0, RW_S) \geq 0$.

Where, composite capital (*k)* and recyclable waste (RW_S) are essential inputs for production of output, q. One traditional good, *y*, is produced in the linear economy model while recyclable good, *q*, is created in the circular economy model, which might be operated at micro and meso (middle layer economy or in-between macro and micro) levels. The *Circular Economy* is based on the '3R' principles: *Reduce, Reuse, and Recycle*. The circular economy reuses waste and reduces resource extractions. Stock of waste accumulation is essential for reusing and recycling resources. Output of q production depends on available stock of recyclable resources in the circular economy. Non-availability of waste stock turns to be a constraint in the circular economy. Consider the circular economy having self-sufficient with proper economic incentives for all possible productive resources and economic activities. This newly produced good, q, of the circular economy (i.e., the recyclable output) is used for only consumption, *c*; payment for input requirements, θR_m, and the rest $h(k, RW_S, R_m) - c - \theta R_m$ is waste measured in terms of output. This is potentially recyclable waste which is used as investment in the circular economy model for further production. Let W_S be the stock of waste and recyclable rate is ϕ. Production activity continues with accumulation of waste stock in the circular economy just like capital formation in the traditional economy which also creates stock of waste that depends on polluting resource, R_m, i.e., $l(R_m)$.

3.3 Stocks Dynamics

Waste is generated through any production processes using polluting resources and is also used as input in the circular economy[5].

Waste accumulation dynamic equation is

$$\dot{W}_S = h(k, R_m, RW_S) - c - \theta R_m + l(R_m) - \delta_W W \qquad (3)$$

Where $\delta_W (\geq 0)$ is depreciation rate of waste, and $l(R_m)$ is waste generating function of polluting resource, R_m with $l_{R_m} > 0$ and $l_{R_m R_m} > 0$ properties. Waste increases with use of

[5] This economy does not focus on traditional capital accumulation. Here, capital accumulation is replaced by waste accumulation.

polluting resource (R_m) at an increasing rate. In the circular economy re-cycling the waste stock, RW_S amount is used to convert it to produce one unit of output q. Reuse and recycle with fully control waste stock dynamic in the circular *economy*. Substituting $RW_S = \phi W_S$ in equation (3) yields the stock of waste accumulation and its dynamic equation in the circular *economy* turns to be

$$\dot{W}_S = h(k, R_m, \phi W_S) - c - \theta R_m + l(R_m) - \delta_W W \quad (4)$$

Pollution is generated due to unused waste stock of last year, i.e., $(1-\phi)W_S$ and polluting resource used in production process, i.e., $\gamma(R_m)$. However, nature absorb certain pollution, i.e., $\delta_p > 0$.

Pollution accumulation dynamic equation is

$$\dot{P} = (1-\phi)W_S + \gamma(R_m) - \delta_p P \quad (5)$$

Where $\gamma_{R_m} > 0$ and $\gamma_{R_m R_m} > 0$

Objective of all these activities is the consumption or need satisfying wants that lead to improvement of wellbeing or welfare of the society.

3.4 Welfare function

For simplicity, this study considers that the household consumes only recyclable output, q, and satisfies his/her utility. The representative household maximizes her (his) instantaneous utility through consumption (c) at each moment, and accumulation of all instantaneous utility discounted by ρ (>0) is his/ her welfare for his/ her entire life span [0, ∞]. So, the traditional objective of the household is

$$\underset{c}{Max} \int_0^\infty U(c) e^{-\rho t} dt \quad (6)$$

Where marginal utility of consumption is positive (i.e., $u_c > 0$) and change of marginal utility of consumption is negative (i.e., $u_{cc} < 0$), discount rate, $\rho > 0$.

So, basic objective of the society is to maximise equation (6) subject to constraints i.e., equation (4) and equation (5) in the circular economy.

4. Results and Analysis

Optimization and economic growth

The Hamiltonian function is

$$H = u(c) + \mu[h(k, R_m, RW_S) - c - \theta R_m + l(R_m) - \delta_W W] + \eta[(1-\phi)W_S + \gamma(R_m) - \delta_p P] \quad (7)$$

FOCs

$$u_c - \mu = 0 \;\; \Rightarrow \;\; u_c = \mu \quad (8)$$

$$\mu(h_{R_m} - \theta + l_{R_m}) + \eta\gamma_{R_m} = 0 \Rightarrow \eta = \mu(\theta - h_{R_m} - l_{R_m}) / \gamma_{R_m} \quad (9)$$

First order conditions (FOC) provide the equilibrium prices of both stocks. Equation (8) shows the shadow price of recyclable waste stock along equilibrium path of marginal utility of consumption while equation (9) displays the ratio of shadow prices of pollution and waste.

Economic growth rate in this Circular Economy is

$$\frac{\dot{c}}{c} = (1/\sigma)[\phi h_{RW_S} - \{(1-\phi)/\gamma_{R_m}\}h_{R_m} + (\theta(1-\phi)/\gamma_{R_m}) - \rho)] \quad (10)$$

Economic growth rate in the circular economy depends directly on marginal productivity of recyclable resources (h_{RW_S}) and rate of recycle of waste (ϕ), and growth rate is reduced due to marginal productivity of polluting resources, h_{R_m}. Crucially economic growth of the circular economy depends on net effect of difference of marginal productivity of recyclable resources (h_{RW_S}) and that of polluting resources, h_{R_m}. Economic growth rate is usually affected by the inter-temporal consumption elasticity (σ), the discount rate (ρ), however, interestingly θ, ϕ $and \gamma$ also influence the economic growth rate in the circular economic system.

Again rearranging equation (10) we get economic growth rate as

$$\frac{\dot{c}}{c} = (1/\sigma)[\phi h_{RW_S} - \{(1-\phi)/\gamma_{R_m}\}(h_{R_m} - \theta) - \rho)] \qquad (11)$$

From equation (11) it is obvious that under payment to the polluting factors (i.e., $h_{R_m} > \theta$) reduces economic growth. So, free polluting resource is harmful for the economy. Under the condition of payment as per marginal productivity of polluting resource ($h_{R_m} = \theta$), economic growth rate turns to be

$$\frac{\dot{c}}{c} = (1/\sigma)[\phi h_{RW_S} - \rho)] \qquad (12)$$

Under restrictive assumptions economic growth rate is still directly connected with marginal productivity of waste and its recycle rate. Equation (12) shows that economic growth rate ($\frac{\dot{c}}{c}$) is the function of marginal productivity of recyclable waste, i.e., $\frac{\dot{c}}{c} = f(h_{RW_S})$, for given parameters ($\sigma$, ϕ, ρ). It is also clear that rate of recycle of waste (ϕ) is directly related to economic growth rate ($\frac{\dot{c}}{c}$). This suggests that the economy grows with increasing waste recycling activities. In this context one obvious proposition or remark can be stated as given below:

Proposition: *Recycling activity raises national income and economic growth.*

Production processes generates waste, which might be recycled for further production that helps to boost up employment and thereby income level increases. So, recycling waste contributes economic growth.

5. Empirical analysis

This section provides empirical validity of the above said theoretical model tangentially[6]. For the empirical testing our basic hypothesis is to find the relationship between income and recycling of waste. This part of the study shows the contribution of waste recycling activity on income generation for selected countries. In this context, this study attempts to find out the relationship between recycle of waste and income across European nations, which have already adopted such activities in last few years.

5.1 Data

For our empirical analysis purpose we have taken data from the Eurostat which is available on OECD website (www.oecd.org or see Eurostat in OECD). The main variable is waste which is measured in kilogram per inhabitant or resident. Recyclable waste is measured in terms of kg per head and also measured in terms of percentage of waste generated in European nations in a year. Considering available major variables in 2014 this paper selects 22 European countries for this study purpose. This study uses basic statistics and econometrics tools for data analysis purpose.

Major waste is generated from industrial production process and its lion share is the mineral waste in 2014 (see Fig 1 and Table A1). Bulgaria is on the top in mineral waste generation and Estonia is on top in other waste (excluding mineral waste) generation[7]. Figure 1 displays a comparative waste generation in EU in 2004 and 2014. It is also noted that average waste generation (excluding major mineral wastes) per inhabitant in European Union (EU-28) reduced to 1755 kg in 2014 from 1907 kg in 2004, and it declined nearly 0.8% per year in EU28. Within the period of 2004-2014, major such waste generation declined in Estonia, Finland, UK, Sweden, Austria, Luxembourg, Cyprus, Spain, Slovenia, Portugal, Hungary, Greece, Romania, Lithuania, Czech Republic and Croatia; while it increased in Belgium, Bulgaria, Poland, Germany, Italy, Ireland and Latvia (Fig 1).

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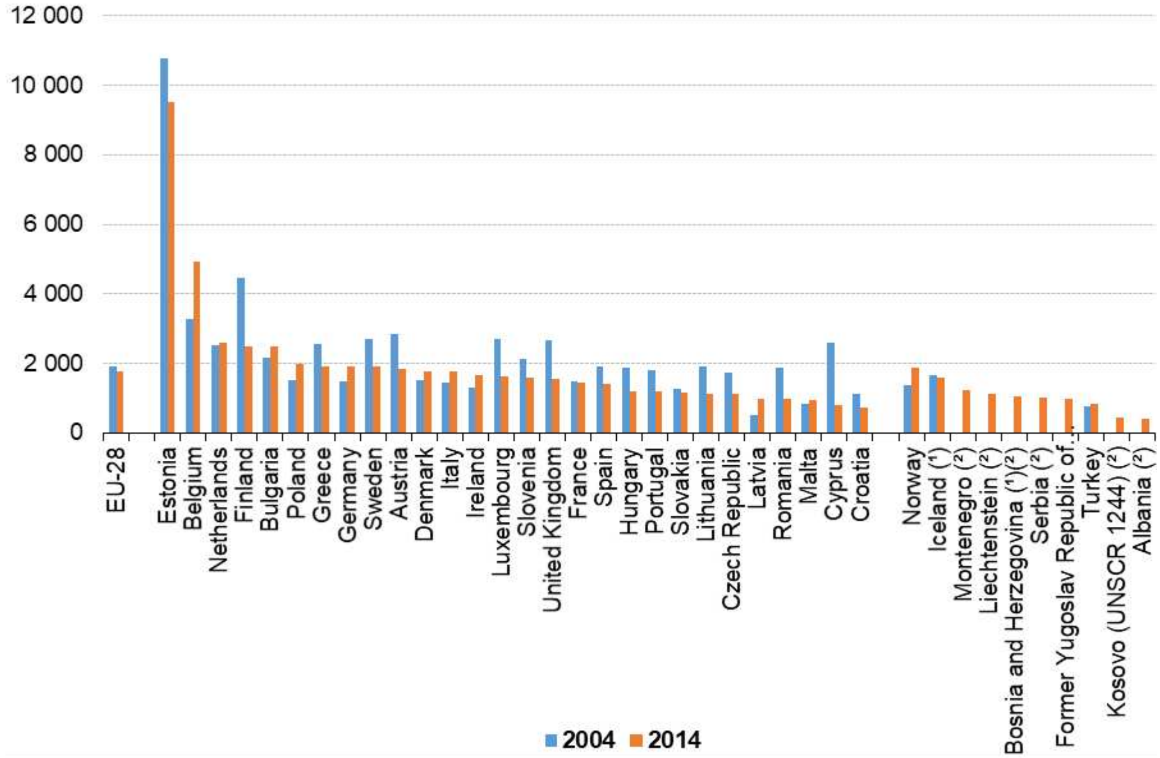
[6] Rigorous data analysis will be done later.

[7] Reason is not clear to us. Need to study on it.

Fig 1: Waste genaration (excluding major mineral wastes) in European Nations in 2004 and 2014.



Source: Eurostat, OECD

5.2 Empirical Analysis

In our empirical exercise we confine with some specific data analysis focusing on recycle of waste and its contribution on the economy in terms of income generation and/or economic growth. Preliminary findings are observed in basic statistics. Table 1 provides summary statistics of income and waste recycles of selected 22 European countries in 2014. Average income growth rate of these nations was 0.71 per cent and average GDP per capita was $ 38704.2 (dollar at constant price 2010) in 2014. Average 106.42 million ton total waste was generated in 22 European countries and in terms of per capita it was 5545.27 kg. Around 38.27% waste recycled or 1754.16 kg waste recycled per head in Europe in 2014.

Table 1: Summary Statistics of 22 European nations in 2014

Variables	Mean	Std. Dev.	Min	Max
GDPpcGrowth (%)	0.71233	2.5815	-8.0176	4.328
GDPpc ($ constant at 2010)	38704.18	16597.57	19666.95	93829.97
Total Waste (million ton)	106.42	107.69	3.72	387.5
Wastepc (kg)	5545.27	4797.88	879	17572
Recycle (%)	40.2	21.13	3.24	76.95
Recycle waste (%)	38.27	50.1	0.34	160.49
Recycle waste pc (kg)	1754.16	1384.5	207.72	5503.88

Recycling activity generates income and thereby boosts up economic growth. Income level and economic growth are directly associated with recycle of waste per capita, other things remain same. Fig 2 shows the scatter diagram of per capita income (horizontal axis) and per capita waste recycle (vertical axis). Applying the ordinary least square (OLS) technique we estimate the relationship between per capita income and per capita waste recycles in 2014. This estimated regression line (as dotted line) is also displayed in Fig 2. For more details, the estimated regression results are given in Table 2. Initially from empirical findings we observe that 7.88 unit of GDP per capita increases with each additional unit of waste recycle per capita. This finding suggests that recycle of additional one unit of waste generates extra 7.88 unit income per capita in the EU in 2014.

Fig 2: Relationship between GDP per capita and per capita waste recycle in EU in 2014

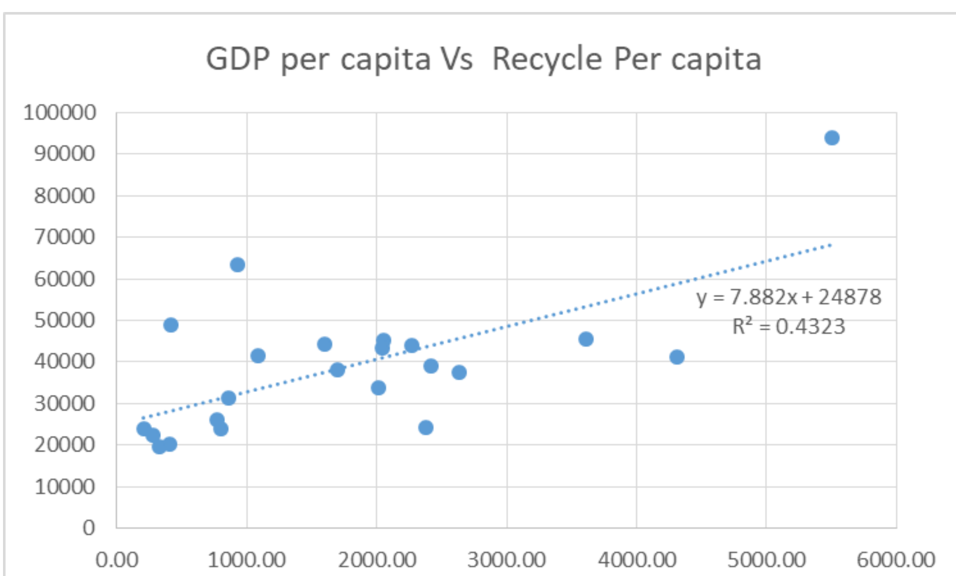


Table 2: OLS Results

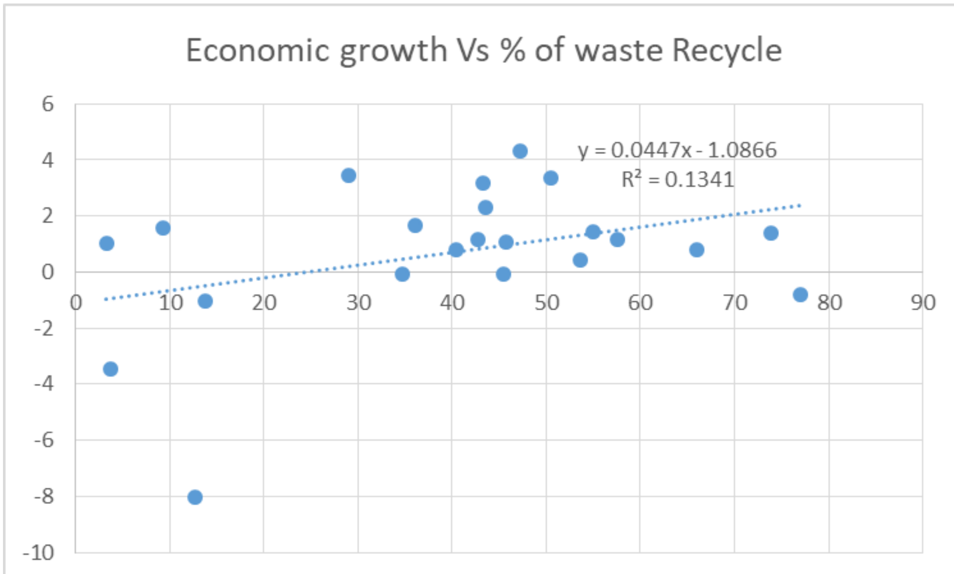
	Model 1	Model 2	Model 3	Model 4
Variables	GDPPC	Log(GDPPC)	Growth	Growth
Constant	24877.9 (5.56)***	8.578 (16.68)***	-0.1641 (-0.18)	-1.0866 (-0.95)
Recycle Waste pc	7.88196 (3.9)***	-	0.0005 (1.24)	-
Log(Recycle Waste pc)	-	0.2683 (3.75)***	-	-
%Waste pc Recycle	-	-	-	0.044745 (1.76)*
R^2	0.4323	0.4123	0.0718	0.1341
Adj.R^2	0.4039	0.3829	0.0254	0.0909
Root MSE	12815	0.30395	2.5485	2.4614
F -Statistics	15.23***	14.03***	1.55	3.1*

Note: Figures in parentheses are t-value. '***', '**', and '*' denote the statistically significant at 1%, 5% and 10%, respectively.

Table 2 provides the OLS results and shows the estimated relationship between Income and Recycle of Waste. Model 1 is the estimated linear relationship between income per capita and per capita waste recycles in EU in 2014 (as mentioned above in Fig 2 also). Model 2 estimates log linear relation of Model 1. The estimated β-coefficient in Model 2 provides the elasticity or response of waste recycle on income level. It is inelastic. As per fitting criteria F statistic of both Model 1 and Model 2 are good fitted models in terms of income generation due to recycle of waste. So, empirical findings support the above said theoretical model.

Next we also check the economic growth and observe that models are poorly fitted in terms of F statistic. Model 3 is insignificant. Model 4 is moderately significant and shows the linear relationship between economic growth and percentage of waste recycles in the EU in 2014. Fig 3 displays the scatter plot along with the estimated relationship between them. The estimated linear regression equation suggests that one percentage of per capita waste recycle contributes around 0.045 per cent in economic growth in the EU in 2014. So, economic growth rises 0.045 per cent for each additional percentage of waste recycle.

Fig 3: Relationship between Economic growth and percentage of waste recycle in production in EU in 2014



6. Conclusion

This study focuses on the circular economic approach for sustainable economic development strategy incorporating the concept of reuse and recyclable resources in endogenous economic growth model framework. Paper highlights recycle of waste which contributes economic growth with reduction of environmental degradation. This paper develops a model which shows an economic growth path in circular economic system where economic growth depends on marginal productivity of waste recycle and continuing economic activities for long time. Economic development path is directly connected with waste recycling activities. The empirical findings also observe it and support our propose model.

Policy makers should be noted that the circular economy requires a system change with parallel actions for produced goods as well as waste resources along the value chain of production and consumption. In the context of circular economy, value creation is decoupled from consumption of finite resources. It should be distinguished between technical and biological cycles[8], which certainly rely on distinct infrastructure building strategies. There are several challenges in terms of policy, technology, social participation to implement the circular economy approach.

This study has several limitations in terms of assumptions and ignores the consumer sentiments. There is a need to change the institution, technology, culture and stable regulatory body for moving towards the circular economic system. Adoption of circular economy will be successful under the condition of technological innovation and social change which is needed to be highlighted in future research agenda.

Acknowledgements: I am grateful to the anonymous referees of this journal who helped bring the paper in its present form by offering valuable comments and suggestions on earlier drafts. Usual disclaimers, however, apply.

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[8]Technological cycles recover and restore products, components and materials through strategies like repair, reuse, remanufacture and recycling; while in biological cycles, nutrients are metabolized and life process regenerate living system, such as soil, plants, or animals, that give rise to materials and other resources.

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Appendix

A.1 Stability Conditions

Now we examine the economic growth saddle path and its stability conditions in the domain of the control and state variables. A stable economic growth saddle path exists in the C - P space under the condition of positive economic growth rate ($\frac{\dot{c}}{c} > 0$); while it is unstable in the C - W_S space. However, a stable saddle path of economic growth exists and stable in the C - W_S space under the condition of positive economic growth more than change of marginal productivity of recyclable resources, i.e., $\frac{\partial \dot{C}}{\partial C} > -\frac{\phi h_{RW_S RW_S}}{h_{RW_S}} (> 0)$.

1a.

$$\begin{vmatrix} \frac{\partial \dot{C}}{\partial C} & \frac{\partial \dot{C}}{\partial P} \\ \frac{\partial \dot{P}}{\partial C} & \frac{\partial \dot{P}}{\partial P} \end{vmatrix} = \begin{vmatrix} (1/\sigma)[\phi h_x - \{(1-\phi)/\gamma\}h_m + (\theta(1-\phi)/\gamma) - \rho] & 0 \\ 0 & -\delta_p \end{vmatrix} < 0 \text{ , } iff \ \frac{\partial \dot{C}}{\partial C} > 0$$

1b.

$$\begin{vmatrix} \frac{\partial \dot{C}}{\partial C} & \frac{\partial \dot{C}}{\partial S} \\ \frac{\partial \dot{S}}{\partial C} & \frac{\partial \dot{S}}{\partial S} \end{vmatrix} = \begin{vmatrix} (1/\sigma)[\phi h_x - \{(1-\phi)/\gamma\}h_m + (\theta(1-\phi)/\gamma) - \rho] & \phi^2 h_{xx} \\ -1 & \phi h_x \end{vmatrix} < 0, \ iff \ \frac{\partial \dot{C}}{\partial C} > -\frac{\phi h_{xx}}{h_x} (> 0)$$

Table A1: Waste generation in EU28 in 2014

Country	**Waste excluding major mineral waste**	**Major mineral waste**	**Total**
Bulgaria	2 474	22 398	24,872
Finland	2 508	15 063	17,572
Sweden	1 901	15 324	17,226
Estonia	9 514	7 073	16,587
Luxembourg	1 617	11 097	12,713
Romania	1 000	7 820	8,820
Netherlands	2 581	5 320	7,901
Austria	1 839	4 701	6,541
Greece	1 928	4 476	6,404
Belgium	4 945	893	5,838
France	1 445	3 468	4,913
Germany	1 908	2 876	4,785
Poland	1 975	2 734	4,710
United Kingdom	1 544	2 341	3,885
Denmark	1 778	1 781	3,558
Ireland	1 681	1 604	3,285
Italy	1 772	846	2,617
Cyprus	792	1 614	2,406
Spain	1 428	950	2,378
Slovenia	1 604	668	2,273
Czech Republic	1 118	1 104	2,223
Lithuania	1 119	996	2,114
Hungary	1 214	474	1,688
Slovakia	1 165	471	1,636
Portugal	1 184	218	1,402
Latvia	1 001	313	1,315
Croatia	723	156	879
Serbia	1 034	5 856	6,890

Source: Eurostat (online data code env_wasgen). Unit: kg per capita