Ability-Biased Technical Change, Economic Growth and the Environment

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Abstract

Technical change is a major driving factor for economic growth and development of economies. During the past decades, there has been acceleration of technical change that has exhibited a skilled labor bias. At the same time, climate change due to anthropogenic activities is posing new challenges to adaptation, impacting differentially the skilled and unskilled labor force. This paper focuses on economic growth and welfare implications due to simultaneous effects of ability-biased technical change and environmental quality change through individual ability-differentiation. We postulate an analytical continuous time endogenous growth model of differentiated human capital (in terms of ability) and endogenous technical change. The model is extended to incorporate the environmental dynamics as a by-product of final good's production. The analysis derives the trade-off between environmental degradation and economic growth on the one hand, while ability-biased technological progress improves environmental quality on the other. The ability differentiation of the individuals and their decision to acquire education affects income distribution, thus generating effects on the level of wage inequality, both within-group and between-group, across distinct categories of individuals. Due to a discouragement effect, rising within-group wage inequality reduces incentives to acquire education for ordinary ability individuals, which in turn, puts a downward pressure on skill supply, and an upward pressure on both within-group and between-group wage inequalities during the period of technological progress. Thus, as economy is growing gradually, at first skill supply increases and then decreases which represents the non-monotonic relationship between the economic growth and skill supply. As a result, economy is converging over the time along the balanced growth path. These results of the analytical model are also validated empirically. The empirical analysis shows that increasing between-group wage inequality decreases economic growth for developed countries whereas, increasing within-group wage inequality promotes economic growth for developing countries, and also the converging or diverging nature of a developing country with respect to a developed country over time due to the simultaneous effects of ability-biased technical change and environmental quality change.

Keywords: *Ability-biased technical change; Endogenous growth; Environmental degradation; Within-group and between-group inequality; Income distribution; Welfare effects; Economic convergence and divergence*

1 Introduction

In the last three decades or so the United States (US) and other advanced economies, like the Organization for Economic Co-operation and Development (OECD) countries, have experienced rapid and biased technological progress with rising wage inequalities, both within [3] and between [4] groups, while also experiencing an environmental quality change. In fact, in recent years, biased technical change along with rising wage inequalities has been observed throughout the world, starting with advanced economies, followed by developing countries. The contemporaneous phenomenon of increasing wage inequalities has been largely induced by information and communication technologies (ICTs), which tend to be mainly work through both directed technical change, i.e., DTC (Acemoglu (1998)) and skill-biased technical change, i.e., SBTC (Galor and Moav (2000)). The recent literature on biased technical change has focused on the role of both the types of skills, i.e., observed educational attainment (captured by DTC) and unobserved inherent ability (captured by ability-biased technical change, ABTC as a part of SBTC), mainly for the evolution of wage inequality during ICT boom. On the one hand, individual skill affects workers' efficiency to produce (Acemoglu (1999)), to absorb new skill-specific technologies (Eicher (1996), Gould and Weinberg (2001)) or to adopt new technologies (Galor and Tsiddon (1997), Galor and Moav (2000)). On the other hand, labour efficiency gets affected by the quality of environment or via the process of environmental change. This environmental or climate change is happening primarily due to anthropogenic activities (Gradus and Smulder (1993)). The impact is likely to be more severe for developing countries (Tol (2009)), on account of lack of resources, adaptation capacities, and geographical disadvantage. In addition, different groups within a country are differentially impacted due to climatic variations (Acemoglu and Dell (2009)), largely due to disparities in their skills and coping capacities. That is, labour efficiency could potentially be affected by environmental quality as well as technological improvement. It is this additional channel of change in economic welfare that forms the basis for motivating this paper.

Moreover, there is a huge and distinct literature that captures the effects of technological improvement on skill-differentiated labor force by only including the observable factor of skill, i.e., educational attainment, while only few works support ABTC (as a part of SBTC frameworks) or the unobserved ability-differentiation. Moreover, while DTC theory does capture the endogenous economic growth process with environmental constraints (see Acemoglu and Hemous (2012)), there is no such literature in

[3]Within-group wage inequality is defined as wage dispersion among workers with the same education and experience.

[4]Between-group inequality is defined as wage dispersion among workers due to different education and experience.

SBTC theory with environmental constraints. In this milieu, our paper aims to analyze the interface between endogenous growth theory (with thrust on ability-biased technological progress) and economics of climate change in an increasingly technology-oriented world.

In this paper, we have extended the Crifo (2008)'s ABTC model in three specific respects. First, we have endogenized the decision making of acquiring education by incorporating a variable representing time spent on education in the individual utility function; second, we define the efficiency functions of labour in terms of economic growth and environmental change which reflects the erosion effects and also the non-monotonic skill supply presented in the model; third, we have incorporated the change in environmental quality into endogenous growth (*à la* Romer, 1996) driven by ability-biased technical change. Specifically, we have modeled environmental pollution as a by-product of production process in an endogenous growth framework. Further, environmental pollution is assumed to a have detrimental effects on the utility of the individuals, in the context of a utility optimization model of an economy with infinitely lived individuals (*à la* Ramsey-Cass-Koopmans) and also on economic growth. Finally, we have tried to empirically show the convergence or divergence of developing countries with respect to developed countries, working simultaneously through the channels of ability-biased technical change and environmental change.

In the model, economic factors, such as within and between inequalities, income distribution, economic growth etc. comes from the same source: the rise in the returns to ability over time. When, over time, the simultaneous effect of technological progress and environmental quality change increases the returns to ability, it reduces the productivity or per unit efficiency of ordinary-ability individuals, even when they choose to become educated. Since producers find it profitable to hire high-ability educated individuals for production, the incentive to acquire education for ordinary-ability individuals is reduced, which is called the discouragement effect, and within-group wage inequality is increased. This rise in within-group wage inequality as a result of the simultaneous effect of technical change and environmental quality change, reduces the relative supply of educated, i.e., skilled labour, thereby driving both within-group and between-group wage inequalities upward over time. As a result, the income is distributed more unevenly across the economy.

To validate our analytical results, we performed an empirical analysis between the two types of economies: developing and developed. We consider a dataset for 62 countries over the time period 1995-2015, where 39 are developed economies and 23 are developing economies. At first, we determine both within and between ability-differentiations respectively by estimating within and between income inequalities using a panel random effect model, by including economic growth, some environmental indicators (environmental vulnerability index, growth of air pollution PM2.5, emission of CO_2, growth of CO_2 emission, pollution index), within and between-group educational attainment ratios, and the interactions of economic growth and environmental indicators with educational attainment ratios as independent variables. We next estimate economic welfare for the whole stylized economy, taking all countries together and later, for developing and developed economies individually using the widely used PCSE (panel corrected standard error) model, by including gross fixed capital formation as a measure of aggregate economic investment, some environmental indicators (environmental vulnerability index, emission of CO_2, growth of CO_2 emission, pollution index), both the types of inequalities and the interactions of environmental indicators and inequalities with educational attainment ratios and ability-differentiations as independent variables. By comparing the estimated economic welfare of developing and developed economies, we find that throughout the period of analysis, 1995-2015, the developing economies are converging with developed economies due to eco-friendly ability-biased technical change.

2 Literature Review

Since this research work relies on a relatively new concept of skill-biased technical change in growth theory, along with the possibility of environmental degradation, we segregate the literature under three broad themes. In the first and second, we review the existing literature on DTC and SBTC respectively. Lastly, the literature on long-run economic growth and the environment is combined and studied in the context of biased technical change paradigms.

2.1 Directed Technical Change (DTC)

The trend in the US wage structure, of increasing wage premium along with increasing skill supply, can be confirmed by looking at Figure 1. Figure 1, which depicts the relationship between college premium and relative supply of college skills over the time period 1939-1996, taking the data from March CPSs (Current Population Surveys) and 1940, 1950 and 1960 censuses.

The standard explanation for the US wage pattern over the past 60 years is in conformity with DTC, first introduced by Daron Acemoglu in 1998. The key effect of DTC is that a rise in the relative supply of skilled workers improves the technologies used by skilled workers. The main focus here is on how DTC is affecting the wage and employment structure through different channels, like the elasticity of substitution

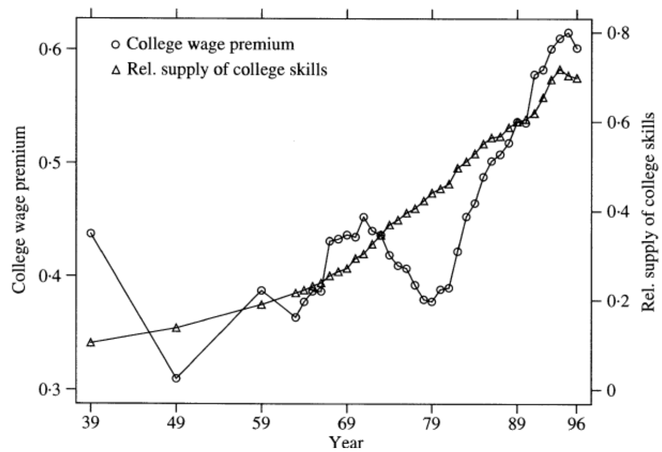

Figure 1: U.S. Wage Structure, 1939-1996

Source: Acemoglu (2002)

between the two intermediate goods, one produced by skilled labour and another produced by unskilled labour, elasticity of substitution between skilled and unskilled labour, opening of trade, technological progress with different types of property rights enforcement, selection of labor force according to the job, creation of skill-specific jobs etc. The brief evolution of literatures through these channels is now discussed.

Acemoglu (1998) explained the US wage structure over the past 60 years through DTC by considering the aggregate production of consumption good (assuming a constant elasticity of substitution (CES) production function), where the consumption good was produced from two complementary intermediate goods, one using skilled labour and another using unskilled labour. The model worked through the use of two effects: the price effect, i.e., the substitution effect, and the directed technology effect, i.e., the market size effect. He found that skill-premium depended on the relative efficiency of these two effects. One of the key observations made was that trade affected the direction of technical change and wage inequality, which was examined through three different scenarios: no directed technical change, directed technical change with property rights enforcement and directed technical change without property rights enforcement. As a result, it was seen that, if US had trade with the less developed countries (LDCs), and sold technologies to the LDC firms, then the market for technologies complementary to unskilled labour increased and the wage inequality of US declined. However if, due to the lack of international property rights protection, US could not sell new technologies to LDC firms, the opening up of trade increased the relative price of skill-intensive goods. This put an upward pressure on the improvement of skill-complementary technologies, and as a result, wage inequality increased more and more.

In addition to this effect of international trade on wage inequality, Acemoglu (2003a) examined that trade with skill-scarce LDCs did not always lead to an increase in the US skill premium; it increased the skill premium in US if and only if the post-trade relative price of skill-intensive goods was greater than the pre-trade relative price in US. He also found that technology became more skill-biased over the past 25 years of this analysis because of the increase in the relative supply of skilled workers in both US and rest of the world, irrespective of the degree of intellectual property rights. Similarly, Kiley (1999) also investigated when and why technology could be biased towards skilled workers and found that the adjustment in the technology mix resulted in slower output growth along the transition path. Also, Xu (2001) generalized these results to the case where both the goods employed both the factors by endogenizing factor bias and sector bias of technological progress. He found that, for two countries, both of which innovated, opening up of trade in final goods would promote SBTC. Then, Acemoglu (1999) explained the endogenous job composition depending on the supply of skilled workers in the market, and the skilled-unskilled productivity gap. He found that, when there was limited supply of skills and a small gap between the productivity levels of skilled and unskilled labour, it was not profitable for a firm to create skill-specific jobs, and as a result, the economy reached a pooling equilibrium where firms created middling (passable) jobs. The alternative to the pooling equilibrium was the separating equilibrium where firms created skill-specific jobs and searched for appropriate candidates. Thus, in a separating equilibrium, jobs for skilled workers were of higher quality and that for unskilled workers were of lower quality than in a pooling equilibrium. Acemoglu and Zilibotti (2001) explained this productivity difference as a result of the technology-skill mismatch. Unlike to Acemoglu (1998), Acemoglu (2002) considered the elasticity of substitution between the two factors, skilled and unskilled labour, to capture the supply side of the economy, and showed that for both, the gross substitute and the gross complementary labour structure- DTC was skill-biased. Also, he introduced the supply side of innovation by considering the cost of different innovations or "the innovation possibilities frontier", which had been earlier introduced by Kennedy (1964). In the separating equilibrium (Acemoglu (1999)), it was seen that firms created skill-specific jobs and searched for appropriate candidates. But, there may be a case of job creation after matching. This possibility was also examined by Acemoglu (2003c) by defining, ability differential in technology adoption from a given world technology frontier, vacancy, and differential unemployment rates across countries. Depending upon the labour market institutional conditions, countries first did the

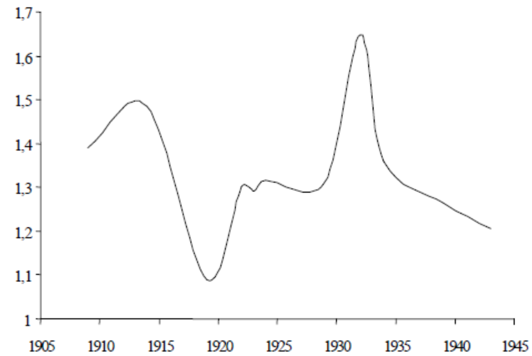

Figure 2: U.S. Wage Inequality in the U.S.

Source: Crifo and Lehmann (2001)

matching, and then, created the jobs according to their profitability.

Thus, all of these channels of DTC resulted in an increase in the wage inequality in US over the period. But, Crifo and Lehmann (2001) discussed about the cyclical trend of wage inequality, i.e., the kuznets curve, according to which, along the process of development, income inequality increased initially, but then declined, which was continuing throughout the decades. The cyclical trend in the beginning of the 1990s that was continuing in the late 1990s and beginning of 2000 could be represented by Figure 2, which was computed by using the data provided by Goldin and Katz (1999), and in this figure Kuznets wage inequality was taken along the vertical axis and year was taken along the horizontal axis. Thus, this increasing and decreasing wage inequality could explain the fact that, technological progress exerted a non-monotonic pressure on wage inequality over the long run.

2.2 Skill-Biased Technical Change (SBTC)

We know skills are two dimensional – education and ability – where the latter is generally unobservable. Acemoglu (1998), Acemoglu (1999), Acemoglu and Zilibotti (2001), Acemoglu (2002), Acemoglu (2003c) mainly showed how DTC was affecting economic welfare through different channels, by only including the observable factor of skill, i.e., the educational level. In SBTC stream, the unobservable quality of skill or ability had been captured, mainly by Galor and Moav (2000).

Galor and Moav (2000) examined the wage inequality within and between groups, by defining the threshold level of ability. Here, the supply of efficient units of labour depended on their respective abilities. They showed that, given the increase in exogenous technological growth rate, the supply of efficient skilled workers increased, and that of unskilled workers decreased, i.e., the threshold value of ability decreased. Thus, a monotonic increase in the rate of technological progress increased both the wage inequalities, within and between groups. Later they endogenized the technological growth, as a monotonic positive linear proportion of skilled workers in the economy, and again derived similar results.

Vandenbussche and Meghir (2006) analyzed the effects of skill-biased technological change across countries through two channels: innovation and imitation. They took into account the composition of human capital and introduced the distance to frontier, i.e., the position of a country from the world technology frontier, and assumed that innovation is relatively more skill-intensive than imitation. As a result, they found that skilled labour had a higher growth-enhancing effect closer to the technology frontier, whereas unskilled labour had a growth-enhancing effect for a technologically backward country. They also found that both skilled and unskilled labour shifted from imitation to innovation activities along the transition path of technological progress. They provided empirical evidence in favour of this result by using a panel data set covering 19 OECD countries over the period 1960-2000. Crifo (2008) explained endogenous technical change as the result of resources devoted to R&D. Also, he distinguished between skilled and unskilled workers by accounting for both, the level of skill and education attainment, along with the ordinary-ability workers. He found that together, the erosion [5] and discouragement effects [6] arising due to SBTC caused a non-monotonic cyclical relationship between wage inequality and skill supply through oscillatory technological transition. This cyclical trend between wage inequality and skill supply is depicted in Figure 3. In Figure 3, the wage differential and relative skill supply in logarithms are taken along the vertical axis and year is taken along the horizontal axis.

Figure 3 shows that, during 1963-1970 and 1990-1995, the relative skill supply and wage inequality appeared to move in the same direction. However, the period 1970-1981 depicted an increase in the college-high school relative supply parallel to a college-high school wage differential while both the periods, 1981-1990 and 1995-2005 exhibited a reverse trend, i.e., a decline in the college-high school relative supply together with an increase in the college-high school wage differential. Further, after

[5] Erosion effect entitled that, the number of efficiency units of labour supply of both unskilled and ordinary-ability workers declined with a rise in the rate of technological progress, but not the number of efficiency units of labour supply of high-ability workers.

[6] Discouragement effect depicts the fact that, although ordinary-ability workers join skilled labour force by acquiring education, firms find it profitable to hire high-ability workers, which in turn discourages the ordinary-ability workers to acquire education.

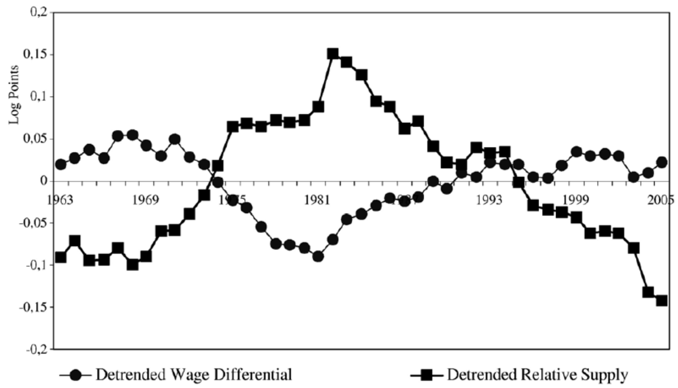

Figure 3: Detrended College-High School Wage Differential and Relative Supply in the U.S.
Source: Autor, Katz, and Kearney (2005)

15 years of continuous rise, the relative skill supply started decreasing in the 1980s, with a significant expansion in the growth rate of Gross Domestic Product (GDP), and the wage inequality (1980-1985), followed by a decline in the relative skill supply (1985-1990). Hence, the period with a decline in the relative skill supply was preceded by an acceleration in the growth rate, and in the wage inequality (mainly within-group, followed by between-group).

Unlike to the Galor and Moav (2000)'s assumption of uniform distribution of ability over the unit interval, Hidalgo (2009) captured the change in the distribution of ability, within each group, on wage inequality. He introduced "new workers" in each year, with a different ability distribution, into the market. This difference was in respect of those who were already engaged in the labour market from the earlier years, and referred to as "old workers". Thus, due to these new entrants, the overall distribution of the group changed, and this had an important effect on wage inequality. Further, Ordine and Rose (2011) captured wage inequality due to over-education or educational mismatch through asymmetric information of individual ability, resulting in inefficient self-selection into education. This over-education or educational mismatch might be due to family background, social environment and opportunity costs of education, which helped to shape schooling ability with heterogeneity in the cost of education, across individuals having similar innate talent. They validated the relevance of university quality and the penalizing effect of mismatch on wage inequality for Italian graduates over the time period 1977-2006. Then, Basu and Mehra (2014) extended Vandenbussche and Meghir (2006)'s work by endogenizing the composition of skilled-unskilled human capital and included an addition effect of an increase in the share of skilled labour force in the overall labour composition. They showed that skilled labour was growth-enhancing for a country performing both innovation and imitation activities and only-innovation activity, while unskilled was growth-enhancing for a country performing only-imitation activity by considering both the cost and benefits associated with skill acquisition. Again, Dupuy (2015) proposed a general equilibrium assignment model of heterogeneous workers to heterogeneous tasks and the impact of technical change on the distribution of wages by endogenizing the population distribution of multidimensional skills, i.e., the skill supply. He showed that, in an economy where workers can respond to SBTC by changing the supply of skill labour, on the one hand, the distinction between intensive and extensive SBTC became impossible to discuss from the data on task assignment alone as an intensive SBTC would lead to a reassignment of tasks to types of skills, and on the other hand, wage inequality was mostly related to the correlation between the types of skills and the respective concentration of skills[7].

Both DTC and SBTC depict the fact that skill-differentiation plays a major role in the process of economic growth and rising wage inequality; no matter whether skill-differentiation is due to educational difference or due to inherent ability difference. This skill-differentiation may be caused by so many human-made factors like, family background, opportunity cost of education, social environment, accessible resources, technological progress, environmental quality etc. In the above sections, we have discussed about many factors affecting economic growth and its distributional implications due to DTC and SBTC. Now in the coming section, we incorporate the environmental dimension in the literature on DTC and SBTC.

2.3 Environment and Long-Run Economic Growth

It had long been observed that there exists a trade-off between environmental degradation and long term economic growth rate, derived by correlating the level of incomes to the indicators of environmental quality like, air pollution, water pollution etc., the so called Environmental Kuznets Curve (EKC)[8] hypothesis (see for example, Grossman and Krueger (1991), Grossman and Krueger (1995), Dell and Olken (2008), Dell (2009)). The survey articles by Xepapadeas (2005), Brock and Taylor (2005) and Ricci (2007) provided a comprehensive review of existing theoretical and empirical research related to the link between economic growth and environmental quality. They focused on how the development of clean technologies and abatement of emissions would impact economic growth and its sustainability. The idea of models

[7]Concentration of skills is calculated as the variance of skills where skills are of different types.

[8]EKC shows the inverted U-shaped relationship between environmental degradation and per capita income.

with technical change was that it could be biased towards some specific sectors in the economy. Depending on that, this bias could be used to redirect technological improvement to cleaner sectors vis-à-vis the dirty sector or vice-versa.

Utilizing the DTC framework propounded by Acemoglu (1998), Smulders and de M. Nooij (2003) developed an endogenous growth model in which energy was an essential input. They modelled innovation as a rational investment behaviour driven by profit maximization, where energy-related innovation was much worse than other types of innovations, and found a fall in economic growth if the energy share was close to its steady state level along the energy conservation path. Again, using Acemoglu (2003b) framework, Maria and Valente (2008) analyzed an economy where natural resource was owned by the economic agents used in the production. They showed that, a steady state would exist in the presence of a non-renewable natural resource used in the production under the decentralized equilibrium. While Grimaud and Rouge (2008) and Acemoglu and Hemous (2012) (henceforth referred to as AABH model) utilized the idea of the equilibrium bias of technical change and formalized different conditions, channels and policy directions through which sustainable growth could be achieved. Grimaud and Rouge (2008) proposed a framework of welfare analysis in a decentralized economy where the consumption good was produced with two resource inputs: one a non-renewable resource, which was polluting and the other being labour resource, a non-polluting one. They tried to show the effects of three associated economic policy tools: a tax on the polluting resource and two research subsidies on environmental quality. They found that the quantity of research was not changed; however, the quality of research was changed in the direction of 'green'[9] research from 'grey'[10] research. In the short-term, the environmental policy was grey-biased, while in the long-term, it was green-biased. Acemoglu and Hemous (2012) provided a more generalized production structure in comparison with Grimaud and Rouge (2008). They integrated the models of DTC and environmental policy by explicitly bringing out the market size effect. They showed the effects of DTC with environmental constraints by using 'dirty' and 'clean' inputs in the final good production. They found three distinct results. At first, when the inputs were sufficiently substitutable, long run growth could be sustainably achieved using temporary policy intervention. Secondly, a delay in intervention became costly, and lastly, the use of an exhaustible resource in dirty input production helped the switch to clean innovation. Thus, with a high elasticity of substitution between the clean and dirty inputs, optimal environmental regulation could be achieved by an immediate switch of R&D resources

[9] 'Green' research represents eco-friendly technological improvement.

[10] 'Grey' research represents technological improvement which degrades environmental quality like, pollution generated from production.

to clean technology, followed by a gradual switch of all production to clean inputs. With respect to the degree of substitution in all the cases, optimal policy included a carbon tax, but research subsidies were even more important to DTC.

To find empirical support, Aghion and Reenan (2012) tested the path dependency in auto industry innovation, distinguishing between dirty and clean patents using firm-level panel data across 80 countries over several decades. They showed that firms were more likely to innovate in clean technologies if they had been previously exposed to clean technologies. Greaker and Heggedahl (2012) introduced long-lived patents into the AABH model and found that the research subsidy for clean technologies became less important than the carbon tax. While under different informational constraints on the behaviour of economic agents, Bondarev and Greiner (2013) compared the models with exogenous and endogenous technical change as well as directed and undirected endogenous technical change using non-linear model predictive control technique. They showed that endogenous technical change yielded lower environmental damages than exogenous technical change with fully informed agents, and a green growth scenario would generate a smaller temperature increase that went along with less output and lower welfare in the case of DTC.

To the best of our knowledge, there is no literature that studies the relationship between environmental quality and economic growth with respect to ability-biased technical change. Most of the work discussed in the above literature captures the effects of technological improvement on skilled and unskilled labour force by only including the observable factor of skill, i.e., the educational level, while only few works support the Ability-Biased Technical Change (ABTC, as a part of the SBTC frameworks). Although, DTC theory does capture the endogenous economic growth process with environmental constraints, there is no research work on SBTC theory with environmental constraints (see Acemoglu and Hemous (2012)). Thus, in this respect, this paper proposes an improvement over the earlier SBTC frameworks. Also, we reckon that environmental change affects skilled and unskilled labour asymmetrically, and thus forms the basis for impacts on skill composition, economic growth and income distribution. This occupies center-stage in our research.

3 Theoretical Analysis

In this section we describe the theoretical model of ABTC (a part of SBTC) with environmental dynamics. The analytical model takes a Romer-type product-variety growth model (see Romer (1996)) in the production side and a Ramsey-Cass-Koopmans economy (see Ramsey (1928), Cass (1965) and Koopmans (1965)) in the consumption side, where households live for an infinite time period and choose consumption and saving to maximize their lifetime utility, subject to an intertemporal budget constraint.

3.1 Basic Framework

The basic model is structured as a closed economy in an endogenous growth framework. The activity of the economy is modelled in continuous time horizon. Let t denotes the index of time. The stylized economy consists of three main sectors in the production side:

- Final good sector: The final good is produced in a competitive market and allocated towards
  - Consumption (by households), C(t)
  - Investment (for research), I(t)
  - Production of a range of intermediate inputs, $i = 1(1)n$ (by firms having patents), X(t)

  Thus, the economic identity is given by,

  $$Y(t) = C(t) + I(t) + X(t), \tag{1}$$

  where $X(t) = n(t)x(t)$.

- Research Sector: The research sector produces innovations in a competitive market structure. These innovations are commercialized and sold by intermediate goods producers to the final good sector for production. Labour is employed only in the final good production.

- Intermediate Good Sector: Intermediate goods sector produces a range of intermediate goods in a monopoly market structure, by using final good as an input under 1:1 relationship.

3.2 Environmental Dynamics

We extend the above mentioned baseline model of Crifo (2008) by incorporating environmental dimension in our basic model of ability-biased technical change. We model environmental pollution as a by-product of the production process in the final good sector.

Thus, the dynamics of the evolution of quality of the environment, in the form of pollution, $P(t)$, are captured by,

$$\dot{P(t)} = \xi(H(t)).Y(t) - \delta.P(t)\ , \tag{2}$$

where, $\xi(H(t))$ is the parameter of the rate of environmental degradation resulting from final good production. Since the technology of production is skill-biased, the rate of environmental degradation is assumed to decrease over time, i.e., $\xi'(H(t)) < 0$, or technological improvement is environmentally friendly. In general, $\xi'(H(t)) \gtreqless 0$ and δ is the rate of environmental regeneration parameter, such that $\delta > 0$. Assume further that, $P(t) \in [0, \bar{P}]$ & $P_0 = 0$ is the quality of the environment in the absence of any human-made (anthropogenic) pollution and $\bar{P}$ is the threshold environmental quality beyond which the economy cannot sustain itself.

The model is now extended by including the environmental impacts on the utility of the representative consumer, such that utility now incorporates the preference over the flow of consumption ($C(t)$), choices of spending time on education ($\tau(t)$), and the total stock of pollution ($P(t)$), i.e., U(C, τ, P).

As is generally assumed, the utility function is increasing and concave in consumption, and decreasing and concave in the variable of time spent on education with the Inada conditions being satisfied. That is,

$$\lim_{C \to \infty} U_C(C, \tau, P) = 0,$$

$$\lim_{\tau \to \infty} U_\tau(C, \tau, P) = 0,$$

$$\lim_{P \to \bar{P}} U_P(C, \tau, P) = -\infty,$$

which ensure the interior solution and utility strictly decreasing and convex in the pollution stock.

3.3 The Final Good Sector

The final good is the numeraire, and it is produced in a competitive market using the technology with skilled workers $H(t)$, unskilled workers $L(t)$, and a range of intermediate goods $x_i(t)$, $i = 0, 1, 2, ..., n(t)$. Thus, the production function is given by:

$$Y(t) = H(t)^{\alpha\beta}\, L(t)^{(1-\alpha)\beta} \int_0^{n(t)} x_i(t)^{1-\beta}\, di\,, \tag{3}$$

where $0 < \alpha < 1$, $0 < \beta < 1$, $i \in [0, n(t)]$ and $n(t)$ is the number of intermediate goods produced at time period t. The representative producer maximizes profit given as:

$$\underset{H(t), L(t), x_i(t)}{\text{Max.}} \quad \Pi(t) = Y(t) - w(t)^s H(t) - w(t)^u L(t) - \int_0^{n(t)} p_i(t)\, x_i(t)\, di\,, \tag{4}$$

where $w(t)^s$ and $w(t)^u$ are the nominal wage rates per efficiency unit of skilled and unskilled labour respectively, and $p_i(t)$ is the nominal price of intermediate good i. The first-order conditions (FOC) of profit maximization representing the inverse demand functions are:

$$\frac{\partial \Pi(t)}{\partial H(t)} = 0 \Longrightarrow w(t)^s = \alpha\beta \, \frac{Y(t)}{H(t)}, \tag{4.1}$$

$$\frac{\partial \Pi(t)}{\partial L(t)} = 0 \Longrightarrow w(t)^u = (1-\alpha)\beta \, \frac{Y(t)}{L(t)}, \tag{4.2}$$

$$\frac{\partial \Pi(t)}{\partial x_i(t)} = 0 \Longrightarrow p_i(t) = (1-\beta)\, H(t)^{\alpha\beta}\, L(t)^{(1-\alpha)\beta}\, x_i(t)^{-\beta}. \tag{4.3}$$

3.4 The Research Sector

The Research and Development (R&D) firms invent new varieties of intermediate goods. They face a two-stage decision making process. In the first stage, they decide whether to devote resources to invent a new design or not. Firms expand these resources if and only if the net present value of future expected profit is at least as large as the R&D expenditure. In the second stage, the individual investors determine the optimal price at which to sell their newly invented good to the producers of the final good. This price determines the flow of profit at each date and, thereby, the present value of profit that was considered in the first stage. We proceed by solving the model backwards.

- Stage II:

  Each intermediate good sector is a monopolistic market. The flow of monopoly profits provides the incentive for invention. Assume that one unit of intermediate good is produced by using one unit of final good and, thus, $x(t)$ units of intermediate good requires $x(t)$ units of final good by firm i. Also, assume that the investor's monopoly position, i.e., the lifetime of a patent of a firm is for an infinite period. Thus, the optimization programme for firm $i \in [0, n(t)]$ is the maximization of firm's profit, $\pi_i(t)$, given as:

$$\underset{x_i(t)}{\text{Max.}} \quad \pi_i(t) = p_i(t)\, x_i(t) \; - x_i(t). \tag{5}$$

  The FOC of the representative firm will be:

$$\frac{\partial \pi_i(t)}{\partial x_i(t)} = 0 \Longrightarrow x_i(t) = (1-\beta)^{2/\beta}\, H(t)^{\alpha}\, L(t)^{(1-\alpha)}. \tag{5.1}$$

Next, substituting the value of $x_i(t)$ from eqn. (5.1) into the demand eqn. (4.3) we get,

$$\begin{aligned} p_i(t) &= \frac{(1-\beta)\, H(t)^{\alpha\beta}\, L(t)^{(1-\alpha)\beta}}{[(1-\beta)^{2/\beta}\, H(t)^{\alpha}\, L(t)^{(1-\alpha)}]^{\beta}} \\ &= \frac{1}{1-\beta}. \end{aligned} \tag{6}$$

Since the price of an intermediate good is a constant mark-up over marginal cost, it turns out that all the intermediate good producers are symmetric in equilibrium. Thus,

$$p_i(t) = p(t) = \frac{1}{1-\beta}\ , \forall\, i, \text{ and} \tag{5.2}$$

$$x_i(t) = x(t) = (1-\beta)^{2/\beta}\, H(t)^{\alpha}\, L(t)^{(1-\alpha)}\ , \forall\, i, \tag{5.3}$$

$$\pi_i(t) = \pi(t) = \frac{\beta}{1-\beta}\, x(t)\ , \forall\, i. \tag{5.4}$$

Again, due to constant mark-up pricing, one can write eqn. (4.3) as:

$$p(t) = (1-\beta)\ \frac{Y(t)}{n(t)x(t)}. \tag{4.4}$$

- Stage I:

  A researcher will find R&D investment attractive if and only if the net present value of patent is at least as large as the R&D expenditure or cost. Assume that the cost to create a new type of product is F, a constant fraction of $Y(t)$.

  Thus, R&D cost $= F$.

  A firm decides to devote resources to R&D if $V(t) \geq F$, where $V(t)$ is the net present value of patent. We assume that there is free entry into the business of being an R&D investor, so that anyone can pay the R&D cost, F, to secure the net present value of the patent, $V(t)$. Thus, the free-entry condition says that, if $V(t) > F$, then an infinite amount of resources would be channeled into R&D at time t, which cannot hold in equilibrium. Alternatively, if $V(t) < F$, then no resources would be devoted to R&D at time t, which implies that the number of goods, $n(t)$ would not change over time. Thus, for a positive level of R&D and growing $n(t)$ at all points of time it must be that,

$$V(t) = F, \quad \forall\, t$$

  Also, the arbitrage condition for innovating new products is given by the condition that the rate of interest times the present value of the patent equals the net present value of future profit plus capital gain or loss as:

$$r(t)V(t) = \pi(t) + \dot{V(t)}$$
$$\implies r(t) = \frac{\pi(t)}{V(t)} + \frac{\dot{V(t)}}{V(t)}.$$

The above equation implies that, in equilibrium, the R&D rate of return equals the addition of the profit rate $\left(\frac{\pi(t)}{V(t)}\right)$ and the rate of capital gain or loss derived from the change in the value of the research firm $\left(\frac{\dot{V}(t)}{V(t)}\right)$.

Thus,

$$F = \frac{\pi(t) + \dot{V}(t)}{r(t)}. \tag{7}$$

Since the R&D cost , F is constant and we have $V(t) = F$, so the free-entry condition implies,

$$\dot{V}(t) = 0.$$

Thus, eqn. (6) becomes,

$$F = \frac{\pi(t)}{r(t)}$$
$$\implies r(t) = \frac{\pi(t)}{F}. \tag{8}$$

Thus, the overall investment level in period t will be:

$$\begin{aligned} I(t) &= \int_0^{n(t)} \frac{\pi_i(t)}{r(t)} di \\ &= \frac{\pi(t)}{r(t)} [n(t) - 0] \\ &= \frac{\pi(t)}{r(t)} n(t). \end{aligned} \tag{9}$$

3.5 Labour Market and Resource Constraints

The size of the population is normalized to one. Individuals differ in their inherent ability: they can have either high-ability or ordinary-ability. The distribution of ability is exogenously given and fixed. However, individuals can acquire education, so that the allocation of workers between skilled and unskilled labour force is endogenous. We use M to denote the proportion of workers that have high-ability (such that the fraction $(1-M)$ refers to ordinary-ability workers), $E(t)$ the fraction of workers with high-ability who choose to become educated and $O(t)$ is the fraction of workers with ordinary-ability who choose to become educated. Both $E(t)$ and $O(t)$ are determined endogenously. The resource constraint on the labour market then becomes,

$$N(t)^{se} + N(t)^{so} + N(t)^{u} = 1, \tag{10}$$

with

$$N(t)^{se} = ME(t), \tag{10.1}$$

$$N(t)^{so} = (1-M)O(t), \tag{10.2}$$

$$N(t)^{u} = M(1-E(t)) + (1-M)(1-O(t)), \tag{10.3}$$

where, $N(t)^{se}$ is the number of skilled workers with high ability, $N(t)^{so}$ is the number of skilled workers with ordinary ability, and $N(t)^{u}$ is the number of unskilled workers. Given the distribution of ability, the choice of becoming educated allows workers with high-ability to supply (or have endowment of) $h(t)$ efficiency per unit of labour at time t and that with ordinary-ability to supply (or have endowment of) $l(t)$ efficiency per unit of labour at time t. Individuals who choose not to acquire skills supply $m(t)$ efficiency per unit of labour at time t. The per unit efficiency levels of each type of workers, i.e., $h(t)$, $l(t)$ and $m(t)$ are exogenously given at a point of time t and these functions are not modelled explicitly for the time being. (These functions will be made more explicit in the following section). So, for now, the parameters $h(t)$, $l(t)$ and $m(t)$ are such that,

$$h(t) > l(t) \geq m(t). \tag{A.1}$$

Thus, the earnings of individuals based on wage rates per efficiency unit of labour will be:

$$W(t)^{se} = h(t)\, w(t)^{s}, \tag{11}$$

$$W(t)^{so} = l(t)\, w(t)^{s}, \tag{11.1}$$

$$W(t)^{u} = m(t)\, w(t)^{u}. \tag{11.2}$$

To become skilled, individuals have to devote a fraction of their unit-time endowment to acquire skills and form human capital (or acquire efficiency). This is the cost of acquiring education or training when new technology enters the market. Let the cost of becoming skilled worker be denoted by $\tau(t)$ $(0 < \tau(t) < 1)$, which mainly depends on the cost of education. This educational cost, in turn, may depend on different factors including environmental pollution, investment in R&D sector etc. over time. Thus, the remaining time left for work is denoted by (1-$\tau(t)$).

Hence, the expected incomes (net of educational costs) for each category of worker will be:

$$\Omega(t)^{se} = (1-\tau(t))\, W(t)^{se}, \tag{12}$$

$$\Omega(t)^{so} = (1-\tau(t))\, W(t)^{so}, \qquad (12.1)$$

$$\Omega(t)^{u} = W(t)^{u}. \qquad (12.2)$$

Depending on the value of $\tau(t)$ from (A.1) we have,
$W(t)^{se} > W(t)^{so} \geq W(t)^{u}$
$\Longrightarrow \ \Omega(t)^{se} > \Omega(t)^{so} \geq \Omega(t)^{u}$ or $\Omega(t)^{se} > \Omega(t)^{so} \leq \Omega(t)^{u}$.

The expected income of an ordinary-ability educated worker may be lower than the expected income of an unskilled worker if $\tau(t)$ is large enough. Then, a situation where ordinary-ability individuals do not acquire any education at all could arise. To rule this out we assume that $\tau(t)$ is not too large so that at least some ordinary-ability individuals acquire education. Since, producers always find it profitable to invest in skilled workers with high-ability, so high-ability skilled workers are always preferred. Thus, there arises a negative incentive or an erosion effect to acquire education for the ordinary-ability individuals, and they may be indifferent in their decision making about acquiring or not acquiring education. So we postulate that,

$$\Omega(t)^{se} > \Omega(t)^{so} = \Omega(t)^{u}. \qquad (A.2)$$

Further, a necessary condition for education acquisition by some ordinary-ability individuals is that, all individuals with high-ability must choose to become educated. That is,

$$E(t) = 1. \qquad (A.3)$$

Thus, eqn. (9) becomes,

$$N(t)^{se} + N(t)^{so} + N(t)^{u} = 1, \tag{13}$$

with

$$N(t)^{se} = M, \qquad (13.1)$$

$$N(t)^{so} = (1-M)O(t), \qquad (13.2)$$

$$N(t)^{u} = (1-M)(1-O(t)). \qquad (13.3)$$

The equilibrium in the labour market implies equality between demand and supply in efficiency units. That is,

$$H(t) = h(t)N(t)^{se} + l(t)N(t)^{so} \quad \text{and} \quad L(t) = m(t)N(t)^{u} \tag{14}$$

The ratio $\frac{\Omega(t)^{so}}{\Omega(t)^{u}}$ from (A.2) satisfies the following condition:

$$\frac{\Omega(t)^{so}}{\Omega(t)^{u}} = 1. \tag{15}$$

Thus, from eqn. (15), the number of workers with ordinary-ability, i.e., $O(t)$ who choose to become educated is derived to be:

$$O(t) = \frac{\frac{\alpha}{1-\alpha}(1-\tau(t)) - \frac{h(t)}{l(t)}\frac{M}{1-M}}{\frac{\alpha}{1-\alpha}(1-\tau(t)) + 1}. \tag{16}$$

That is, *from the two assumptions, (A.2) and (A.3) implying that all high-ability individuals acquire education and at least some ordinary-ability individuals acquire education, even though ordinary-ability individuals are indifferent between the choice of acquiring education and not acquiring education, the size of educated ordinary-ability work force depends on the per unit efficiency levels and the time devoted for education.*

Since there exist three different types of individuals, high-ability educated, ordinary-ability educated and uneducated or unskilled individuals, the average consumption of these three types of individuals needs to be considered. This average consumption ($\bar{C}(t)$) equals the aggregate consumption of the economy ($C(t)$) as the total population is normalized to one. Thus, from Lemma 1 and economic identity given in eqn. (3.1) we have the representative consumption of the economy in the aggregate as,

$$C(t) = \bar{C}(t) = \beta(1-\beta)^{2(1-\beta)/\beta}\left(2-\beta-\frac{1-\beta}{r(t)}\right)\left[\frac{\alpha}{1-\alpha}(1-\tau(t))\right]^{\alpha}\left[\frac{\alpha}{1-\alpha}(1-\tau(t))+1\right]^{-1}$$
$$[h(t).M + l(t).(1-M)]\left(\frac{m(t)}{l_t}\right)^{1-\alpha} n(t), \tag{17}$$

where $r(t)$ is given by

$$r(t) = \frac{\beta}{F}(1-\beta)^{\frac{2}{\beta}-1}\left(\frac{\alpha}{1-\alpha}(1-\tau(t))\right)^{\alpha}\left(\frac{\alpha}{1-\alpha}(1-\tau(t))+1\right)^{-1}[h(t).M+l(t).(1-M)]\left(\frac{m(t)}{l(t)}\right)^{1-\alpha}. \tag{8.1}$$

3.6 Households' Decisions Without Environmental Constraints

Given three different types of individuals in the economy, an average/ representative consumer makes his/ her preferences over the average consumption $\bar{C}(t)$ and the time devoted on education $\tau(t)$. So, a representative consumer determines his/ her preferences by maximizing the utility function subject to an intertemporal budget constraint over an infinite time period such that,

$$\underset{C(t),\tau(t)}{\text{Max.}} \qquad U = \int_0^\infty e^{-\rho t} \; U(C,\tau)\, dt$$

$$\text{subject to} \quad \int_0^\infty e^{-R(t)} \; C(t)\, dt \quad \leq \quad \int_0^\infty e^{-R(t)} \; \bar{\Omega}(t)\, dt \; ,$$

where, $\bar{C}(t)$ is the average consumption at time t, $\bar{\Omega}(t)$ is the aggregate expected net income at time t, ρ is the utility discount rate ($\rho > 0$), and

$$R(t) = \int_{r=0}^{t} r(t)\, dt \; ,$$

with $r(t)$ being the real interest rate at time t, so that $e^{-R(t)}$ is the discount factor, and the average consumption is given by eqn. (3.16) and expected net income at time period t is given as,

$$\bar{\Omega}(t) = (1-\alpha)\beta(1-\beta)^{2(1-\beta)/\beta} \; \left[\frac{\alpha}{1-\alpha}(1-\tau(t))\right]^{\alpha} \; [h(t).M + l(t).(1-M)] \left(\frac{m(t)}{l(t)}\right)^{1-\alpha} \; n(t) \; . \quad (18)$$

Now, the lagrangian function and the necessary FOCs of the maximization problem of the consumer as depicted earlier will be respectively derived as,

$$L_1 = \int_0^\infty e^{-\rho t}\, U(C,\tau)\, dt + \lambda_1 \, [\int_0^\infty e^{-R(t)}\, \bar{\Omega}(t)\, dt - \int_0^\infty e^{-R(t)} C(t)\, dt] \quad (19)$$

and

$$e^{-\rho t} U_C - \lambda_1 e^{-R(t)} = 0 \implies e^{-\rho t} U_C = \lambda_1 e^{-R(t)} \; , \quad (19.1)$$

$$e^{-\rho t} \; U_\tau + \lambda_1 e^{-R(t)} \, \frac{\partial \bar{\Omega}(t)}{\partial \tau(t)} = 0 \implies e^{-\rho t} U_\tau \, (1-\tau(t)) = \lambda_1 e^{-R(t)}.\alpha.\bar{\Omega}(t) \; . \quad (19.2)$$

In this optimization problem, the control variables are $\bar{C}(t)$ and $\tau(t)$ and the state variable is the savings (net income left after consumption), say $S(t)$ which is the source of investment or net capital stock. So, the transversality condition is given by:

$$\lambda_1(T).S(T) = 0$$

By taking the natural logarithm of eqns. (19.1) and (19.2) and differentiating with respect to time t, the growth path of consumption (C(t)) and the growth path of time spent on education ($\tau(t)$) respectively to be:

$$\frac{\dot{C(t)}}{C(t)} = \left(-\frac{U_{CC}}{U_C} C(t)\right)^{-1} \left(r(t) - \rho + \frac{U_{C\tau}}{U_C} \dot{\tau(t)}\right) \; , \quad (20)$$

$$\frac{\dot{\tau(t)}}{1-\tau(t)} = \left((1-\alpha) - \frac{U_{\tau\tau}}{U_\tau}(1-\tau(t))\right)^{-1} \left(r(t) - \rho + \frac{U_{\tau C}}{U_\tau} \dot{C(t)}\right) \; . \quad (21)$$

By assuming a constant intertemporal elasticity of substitution (CIES) utility function,

$$U(C,\tau) = \frac{C^{1-\theta}-1}{1-\theta} + \frac{(1-\tau)^{1-\phi}-1}{1-\phi}\ , \tag{22}$$

where, $0 < \theta < 1$ and $0 < \phi < 1$, we have the consumption growth path and the growth path of time spent on work force respectively to be:

$$\frac{\dot{C(t)}}{C(t)} = \frac{1}{\theta}\left[r(t)-\rho\right], \qquad \text{(from eqn. (20))} \tag{23}$$

$$\frac{\dot{\tau(t)}}{1-\tau(t)} = \frac{1}{1-\alpha-\phi}\left[r(t)-\rho\right]. \qquad \text{(from eqn. (21))} \tag{24}$$

Now, for progressive growth path of the economy we must have, $\frac{\dot{C(t)}}{C(t)} \geq 0$ for which it is necessary and sufficient that,

$$r(t)-\rho \geq 0, \qquad (A.4)$$

That is, *the rate of interest should be greater than or equal to the utility discount rate or the rate of time preference.*. Further, $\frac{\dot{\tau}(t)}{1-\tau(t)} \leq 0$ for which it is necessary and sufficient that,

$$1-\alpha \leq \phi, \qquad (A.5)$$

That is, *the share of unskilled workers in final good production should be less than or equal to the intertemporal elasticity of substitution of the variable time left after spending on education, i.e., time spent for contributing to work force.* Given this parametric restriction, $\dot{\tau(t)}$ is negative, so that more and more ordinary-ability individuals join the skilled work force.

Intuitively, these conditions imply the following. If the rate of interest ($r(t)$) is less than the utility discount rate, which denotes the discount factor of sacrificing utility today for the future, no one will save or invest today for the future, and over an infinite time horizon, the economy will not sustain growth, or will break down. Thus, for sustainable and progressive economic growth one must have the condition given in (A.4) to be met. Further, the intertemporal elasticity of substitution shows the net effect on the present value to the variable time spent for work if one decides to work in future instead of current/ present time. So, working in the future means acquiring education in present. Thus, if $1-\alpha > \phi$ then for the unskilled workers it is more profitable to not acquire education in the present as they are getting a higher share in final good production. Similarly, for equality they are indifferent between acquiring and not acquiring education, implying that ABTC theory breaks down. So, for sustainable and progressive economic growth under ABTC one must also have the condition given in (A.5) to be satisfied.

3.7 Equilibrium

In equilibrium, we have demand equal to supply in all the sectors. The labour market equilibrium is represented by eqns. (13), (14) and (16) along with the necessary conditions given in (A.1), (A.2), and (A.3). Thus, the size of educated ordinary-ability work force, i.e., O(t) increases, and correspondingly, the size of unskilled work force decreases over time. Mathematically, these dynamics are captured by:

$$\frac{\dot{O(t)}}{O(t)} = -\frac{\alpha}{1-\alpha}\dot{\tau(t)}\frac{1+\frac{h(t)}{l(t)}\frac{M}{1-M}}{(\frac{\alpha}{1-\alpha}(1-\tau(t))+1)(\frac{\alpha}{1-\alpha}(1-\tau(t))-\frac{h(t)}{l(t)}\frac{M}{1-M})}, > 0; \qquad (\text{as } \dot{\tau(t)} < 0 \text{ from (A.5)}) \tag{25}$$

and, hence, the size of unskilled work force decreases over time as $\frac{\dot{N(t)^u}}{N(t)^u} = -\frac{\dot{O(t)}}{1-O(t)}$.

Also, from the production and consumption sides, the aggregate levels of final output, consumption and investment should be equal. So, by taking the natural logarithm of eqn. (17) and differentiating with respect to time t, and equating with eqn. (23) we get the growth path of the economy to be:

$$\frac{\dot{n(t)}}{n(t)} = \frac{1}{\theta}\left[r(t)-\rho\right] + \left[1+\frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right]\left[\frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1}\right]. \tag{26}$$

Now, the balanced growth path (BGP) of the economy can be characterized as,

$$\frac{\dot{O(t)}}{O(t)} = 0 \tag{27}$$

and,

$$\frac{\dot{n(t)}}{n(t)} = 0\,, \qquad \text{(which is convergent)} \tag{28}$$

as along the BGP we have $\frac{\dot{C(t)}}{C(t)} = 0$ and $\frac{\dot{\tau(t)}}{1-\tau(t)} = 0$.

Further, the production function given in eqn. (3) can be written as,

$$Y(t) = H(t)^{\alpha}L(t)^{1-\alpha}(1-\beta)^{2(1-\beta)/\beta}n(t) \tag{3.1}$$

Also,

$$Y(t) = (1-\beta)^{2(1-\beta)/\beta}\left[\frac{\alpha}{1-\alpha}(1-\tau(t))\right]^{\alpha}\left[\frac{\alpha}{1-\alpha}(1-\tau(t))+1\right]^{-1}\left[h(t).M+l(t).(1-M)\right]\left(\frac{m(t)}{l(t)}\right)^{1-\alpha}n(t) \tag{3.2}$$

Thus, by taking the natural logarithm of eqn. (3.2) and differentiating with respect to time t we get the growth path of final good production as:

$$\frac{\dot{Y(t)}}{Y(t)} = \frac{1}{\theta}\left[r(t)-\rho\right] + \left(\frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right)\left[\frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1}\right]. \tag{29}$$

Thus, along the balanced growth path the final good production will grow as:

$$\frac{\dot{Y(t)}}{Y(t)} = 0, \tag{30}$$

Again substituting the value of $\pi(t)$ from eqn. (5.4) in eqn. (9) and taking the natural logarithm on both sides and differentiating with respect to time, t, we have the aggregate investment growth path as:

$$\frac{\dot{I(t)}}{I(t)} = \frac{\dot{n(t)}}{n(t)}. \tag{31}$$

Thus, aggregate investment will grow at the same rate as overall economic growth.

Further, substituting the value of $x(t)$ from eqn. (5.3) in the equation $X(t) = n(t)x(t)$ and taking the natural logarithm on both sides and again differentiating with respect to time, t, the growth path of each intermediate inputs production is found to be:

$$\frac{\dot{X(t)}}{X(t)} = \frac{\dot{Y(t)}}{Y(t)}. \tag{32}$$

Thus, individual intermediate inputs production will also be growing at the same rate as final good production.

Hence, along BGP in the long-run, the growth path of size of educated ordinary-ability workers given in eqn. (27), the economic growth path shown in eqn. (28), and the growth paths of all its sectors, i.e., the growth paths of final good production (given in eqn. (30)), aggregate consumption (given in eqn. (23)), aggregate investment (given in eqn. (31)) and intermediate inputs production (given in eqn. (32)) are progressive and convergent.

Thus, *BGP of the economy and its each sectors are stagnant, though convergent in long-run.*

3.8 Extensions of the Basic Theoretical Model

We now extend our basic analytical model in two respects: one is by defining the per unit efficiency level functions, $h(t)$, $l(t)$ and $m(t)$, as function of technical change and environmental quality change, and second, by explicitly incorporating the environmental dynamics in the households' preference structure.

3.8.1 Endogenizing Efficiency Functions of Labour

In a dynamic framework, any change in the economy, such as technological change ($\dot{n(t)}$) and environmental change ($\dot{P(t)}$) (for now, the environmental dynamics are not modelled explicitly), exert an erosion effect on the efficiency units of labour supplied by unskilled and ordinary-ability individuals. We postulate that there is no erosion effect for high-ability workers, since they can cope with or adapt to any such changes much more easily, whereas others will take time to adapt to these changes. To formalize the erosion effect, we consider that per unit efficiency levels of the unskilled and ordinary-ability workers are decreasing over the time. Thus we have,

$h(t) = h$,
$l(t) = l_t\left(\dot{n(t)}, \dot{P(t)}\right)$,
$m(t) = m_t\left(\dot{n(t)}, \dot{P(t)}\right)$,
with, $l(t) > m(t)$,
$\dot{l(t)} \leq \dot{m(t)} < 0$,
and $\dot{h(t)} = 0$. (A.6)

So, by taking the natural logarithm of eqn. (17) and differentiating with respect to time t, and equating with eqn. (23) we get the growth path of the economy to be:

$$\frac{\dot{n(t)}}{n(t)} = \frac{1}{\theta}\left[r(t)-\rho\right] + \left[1 + \frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right]$$
$$\left[\frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1} - \frac{M.\dot{h(t)}+(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)} + (1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right)\right]. \tag{33}$$

Accordingly, the BGP of the economy can be characterized as,

$$\frac{\dot{O(t)}}{O(t)} = \frac{\frac{M}{1-M}\frac{h(t)}{l(t)}\frac{\dot{l(t)}}{l(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t)) - \frac{h(t)}{l(t)}\frac{M}{1-M}} < 0 \tag{34}$$

and,

$$\frac{\dot{n(t)}}{n(t)} = \left[1 + \frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right]\left[(1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right) - \frac{(1-M)\dot{l(t)}}{h(t).M+l(t).(1-M)}\right], \tag{35}$$

which is progressive as $\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)} > 0$ and $\dot{l(t)} < 0$ from (A.6).

To have convergent economic growth, we must have:

$$1 + \frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}} < 1$$
$$\implies \frac{2-\beta}{2-\beta-\frac{1-\beta}{r(t)}} < 1$$
$$\implies 1-\beta < r(t). \qquad (A.7)$$

That is, *the rate of interest must be higher than the share of intermediate goods in the final good production;*

and

$$\frac{\dot{l(t)}}{l(t)} < 1 \qquad \text{and} \qquad \frac{\dot{m(t)}}{m(t)} < 1,$$

which indicates that the erosion effect will become lesser than its absolute efficiency levels over time. For more innovation of intermediate goods it is necessary that the rate of interest be high enough. If, however, the rate of interest is lower than the share of intermediate goods in the final good production, then there will be less incentive for innovation activity in the intermediate goods sector, and only the patents for old goods will remain in the market. As a result, the economy will be stagnant or caught in a trap. So, for progressive economic growth, we must have rate of interest higher than the share of intermediate goods in final good production.

Next, for the balanced growth path of the economy to be convergent, we must also have

$$0 < \frac{\dot{n(t)}}{n(t)} < 1.$$

As economy progresses over time, the final good production, aggregate investment and intermediate inputs production will also change. By taking the natural logarithm of eqn. (3.2) and differentiating with respect to time t we derive the growth path of final good production as:

$$\begin{aligned} \frac{\dot{Y(t)}}{Y(t)} &= \frac{1}{\theta}\left[r(t)-\rho\right] + \left(\frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right) \\ &\left[\frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1} - \frac{M.\dot{h(t)}+(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)} + (1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right)\right]. \end{aligned} \tag{36}$$

Thus, along BGP the final good production will grow as:

$$\frac{\dot{Y(t)}}{Y(t)} = \frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\left[(1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right) - \frac{(1-M)\dot{l(t)}}{h(t).M+l(t).(1-M)}\right], \tag{37}$$

which depends on the per unit efficiency levels of individuals and is convergent in the long-run.

Again, substituting the value of $\pi(t)$ from eqn. (5.4) in eqn. (9) and taking the natural logarithm on both sides and differentiating with respect to time, t, we have the aggregate investment growth path as:

$$\frac{\dot{I(t)}}{I(t)} = \frac{\dot{n(t)}}{n(t)}. \tag{38}$$

That is, aggregate investment will grow at the same rate as overall economic growth.

Further, substituting the value of $x(t)$ from eqn. (5.3) in the equation $X(t) = n(t)x(t)$ and taking the natural logarithm on both sides and differentiating with respect to time, t, we have the growth path of intermediate inputs production as:

$$\frac{\dot{X(t)}}{X(t)} = \frac{\dot{Y(t)}}{Y(t)}. \tag{39}$$

Thus, intermediate inputs production will also grow at the same rate as that of final good production.

Hence, along BGP in the long-run, the economic growth path shown in eqn. (35), and the growth paths of all its sectors, i.e., the growth paths of final good production (given in eqn. (37)), aggregate consumption (given in eqn. (23)), aggregate investment (given in eqn. (38)) and intermediate inputs production (given in eqn. (39)) are progressive and convergent, although the size of educated ordinary-ability workers is decreasing (given in eqn. (34)) with simultaneous technical and environmental quality change.

Thus, *BGP of the economy and its each sectors are convergent in long-run and depending solely on individual's per unit efficiency levels and its growth, although size of skilled labour force decreases gradually as size of educated ordinary-ability workers declines.*

3.8.2 Incorporating Environmental Dynamics in Households' Decision

We incorporate the environmental pollution variable in the utility function such that the representative consumer will now make decision over consumption, educational acquisition and pollution level. At the private equilibrium, the representative consumer treats the pollution level as given and solves the problem as,

$$\begin{aligned} &\underset{C(t),\tau(t)}{\text{Max.}} \qquad U = \int_0^\infty e^{-\rho t}\ U(C,\tau,P)\,dt \\ &\text{subject to} \quad \int_0^\infty e^{-R(t)}\ C(t)\,dt \quad \leq \quad \int_0^\infty e^{-R(t)}\ \bar{\Omega(t)}\,dt\,. \end{aligned}$$

The lagrange function and the necessary FOCs of the maximization problem of the representative consumer will be:

$$L_2 = \int_0^\infty e^{-\rho t}\,U(C,\tau,P)\,dt + \lambda_2\left[\int_0^\infty e^{-R(t)}\,\bar{\Omega(t)}\,dt - \int_0^\infty e^{-R(t)}C(t)\,dt\right], \tag{40}$$

and

$$e^{-\rho t}\,U_C - \lambda_2 e^{-R(t)} = 0 \implies e^{-\rho t}U_C = \lambda_2 e^{-R(t)}\,, \tag{40.1}$$

$$e^{-\rho t}\,U_\tau + \lambda_2 e^{-R(t)}\,\frac{\partial\bar{\Omega(t)}}{\partial\tau(t)} = 0 \implies e^{-\rho t}U_\tau\,(1-\tau(t)) = \lambda_2 e^{-R(t)}.\alpha.\bar{\Omega(t)}\,. \tag{40.2}$$

Although the representative consumer has preferences defined over environmental pollution, they make decision over average consumption $\bar{C(t)} = C(t)$ and time devoted on education $\tau(t)$ only; they have no control over the level of pollution. By taking the natural logarithm of eqns. (40.1) and (40.2) and differentiating with respect to time t, we get the growth paths of consumption ($C(t)$) and time spent for work force $(1-\tau(t))$ to be:

$$\frac{\dot{C(t)}}{C(t)} = \frac{1}{\eta_C}\left[r(t) - \rho + \frac{U_{C\tau}}{U_C}\dot{\tau(t)} + \frac{U_{CP}}{U_C}\dot{P(t)}\right], \tag{41}$$

where, $\eta_C = \left(-\frac{U_{CC}}{U_C}C(t)\right)$, and

$$\frac{\dot{\tau(t)}}{1-\tau(t)} = \frac{1}{\eta_\tau + 1 - \alpha}\left[r(t) - \rho + \frac{U_{\tau C}}{U_\tau}\dot{C(t)} + \frac{U_{\tau P}}{U_\tau}\dot{P(t)}\right], \tag{42}$$

where $\eta_\tau = \left(-\frac{U_{\tau\tau}}{U_\tau}(1-\tau(t))\right)$.

We now put some more structure on our framework by considering a constant intertemporal elasticity of substitution (CIES) utility function of the form:

$$U(C,\tau,P) = \frac{C^{1-\theta}-1}{1-\theta} + \frac{(1-\tau)^{1-\phi}-1}{1-\phi} - \frac{1}{\gamma}P^\gamma \tag{43}$$

where, $0<\theta<1$, $0<\phi<1$ and $\gamma>1$.

This yields the paths for $C(t)$ and $\tau(t)$ respectively as,

$$\frac{\dot{C(t)}}{C(t)} = \frac{1}{\theta}\left(r(t)-\rho\right), \qquad \text{(from eqn. (41))} \tag{44}$$

$$\frac{\dot{\tau(t)}}{1-\tau(t)} = \frac{1}{1-\alpha-\phi}\left(r(t)-\rho\right). \qquad \text{(from eqn. (42))} \tag{45}$$

Thus, at the steady-state, the growth paths and the levels of $C(t)$ and $\tau(t)$ are same as without the environmental dynamics. Only the approach towards the growth paths will now be different. The steady-state stock of pollution in this case is uniquely determined from the equilibrium of the economic system as,

$$P^* = \xi(H(t))\,\frac{Y(t)}{\delta}. \tag{46}$$

Given that the problem of environmental pollution is large and looming today, and the aim is to make the growth process more sustainable in the steady-state, it must be that over time $\dot{P(t)} = 0$, i.e., growth should entail no further increase in environmental pollution. So, from a long-run perspective, we must have,

$$\dot{P(t)} = 0 \implies \xi(H(t)).Y(t) = \delta.P(t)\,. \qquad \text{(from eqn. (2))}$$

Taking the natural logarithm and differentiating with respect to time t, we get the economic growth path with environmental dynamics to be:

$$\frac{\dot{n(t)}}{n(t)} - \frac{\dot{P(t)}}{P(t)} = -\frac{\xi'(H(t))}{\xi(H(t))}\dot{H(t)} + \frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1} - \frac{M.\dot{h(t)}+(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)} + (1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right)$$

$$\implies \frac{\dot{n(t)}}{n(t)} = -\frac{\xi'(H(t))}{\xi(H(t))}\dot{H(t)} + \frac{\alpha\dot{\tau(t)}}{1-\tau(t)} - \frac{\frac{\alpha}{1-\alpha}\dot{\tau(t)}}{\frac{\alpha}{1-\alpha}(1-\tau(t))+1} - \frac{M.\dot{h(t)}+(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)} + (1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right), \tag{47}$$

which is a function of the change in environmental degradation due to skill supply, i.e, $\xi'(H(t)).\dot{H(t)}$, change in the time spent on education, i.e., $\dot{\tau(t)}$ and changes in the efficiency levels, i.e., $\dot{h(t)}$, $\dot{l(t)}$ and $\dot{m(t)}$. In eqn. (47) along BGP, we have $\dot{\tau(t)} = 0$ and so, the second and third terms vanish, and $\dot{h(t)} = 0$ from (A.6) as no erosion effect exists for high-ability individuals. Thus, the balanced economic growth path with environmental dynamics turns out to be:

$$\frac{\dot{n(t)}}{n(t)} = (1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right) - \frac{(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)} - \frac{\xi'(H(t))}{\xi(H(t))}\dot{H(t)}\ . \tag{48}$$

For a progressive economic growth process we must have $\frac{\dot{n(t)}}{n(t)} \geq 0$. In eqn. (48), the first two terms are positive from (A.6). So, economic growth with environmental dynamics to be progressive solely depends on the signs of ξ' and $\dot{H(t)}$. Here, the have the following alternative situations might arise.

Case I: When $\dot{H(t)} < 0$ and $\xi'(H(t)) > 0$, we have $\frac{\dot{n(t)}}{n(t)} > 0$, i.e., progressive economic growth.

Case II: When $\dot{H(t)} < 0$ and $\xi'(H(t)) < 0$, the sign of $\frac{\dot{n(t)}}{n(t)}$ is ambiguous. In that case, progressive economic growth is possible if and only if the change in environmental degradation, i.e., $\frac{\xi'}{\xi}\dot{H(t)}$ is small enough.

Case III: When $\dot{H(t)} = 0$ or $\xi'(H(t)) = 0$, we have $\frac{\dot{n(t)}}{n(t)} > 0$. Since total skill supply cannot be equal to zero, so we have $\xi'(H(t)) = 0$ which means there is constant environmental degradation.

Case IV: When $\dot{H(t)} > 0$ and $\xi'(H(t)) > 0$, then also for sustainability of economic growth, the change in environmental degradation has to be small enough. Otherwise, the sign of $\frac{\dot{n(t)}}{n(t)}$ will be ambiguous.

Case V: When $\dot{H(t)} > 0$ and $\xi'(H(t)) < 0$, we have $\frac{\dot{n(t)}}{n(t)} > 0$.

Now, comparing eqns. (35) and (48) we have,

$$\frac{\dot{n(t)}}{n(t)}|_{woenv.} - \frac{\dot{n(t)}}{n(t)}|_{wenv.} = \left(\frac{\frac{1-\beta}{r(t)}}{2-\beta-\frac{1-\beta}{r(t)}}\right)\left[(1-\alpha)\left(\frac{\dot{l(t)}}{l(t)} - \frac{\dot{m(t)}}{m(t)}\right) - \frac{(1-M).\dot{l(t)}}{h(t).M+l(t).(1-M)}\right] + \frac{\xi'(H(t))}{\xi(H(t))}\dot{H(t)}. \tag{49}$$

This difference between economic growth rates without environment (woenv.) and with environment (wenv.) shows the existence of a trade-off between economic growth and environmental degradation.

This trade-off mainly depends on the signs of ξ' and $\dot{H(t)}$, as the other terms are positive from eqn. (35). That is,

Case I: When $\dot{H(t)} < 0$ and $\xi'(H(t)) > 0$, the sign of trade-off in eqn. (49) is ambiguous. However, due to sustainable economic growth as the change in environmental degradation $\frac{\xi'}{\xi}\dot{H(t)}$ should be less, the trade-off become positive, i.e, environmental degradation offsets economic growth.

Case II: When $\dot{H(t)} < 0$ and $\xi'(H(t)) < 0$, eqn. (49) becomes positive.

Case III: When $\dot{H(t)} = 0$ or $\xi'(H(t)) = 0$, eqn. (49) becomes positive. Since total skill supply cannot be equal to zero, we have $\xi'(H(t)) = 0$ which means there is constant environmental degradation and due to constant environmental degradation, economic growth is offset by environment.

Case IV: When $\dot{H(t)} > 0$ and $\xi'(H(t)) > 0$, we have positive trade-off.

Case V: When $\dot{H(t)} > 0$ and $\xi'(H(t)) < 0$, the sign of eqn. (49) is ambiguous like Case I.

But, along BGP it has been shown that the change in skill supply, i.e., $\dot{H(t)}$ is negative due to the presence of both – erosion and discouragement – effects in ABTC as depicted below,

$$\begin{aligned}\dot{H(t)} &= M.\dot{h(t)} + (1-M)[\dot{l(t)}O(t) + l(t)\dot{O(t)}] \qquad \text{(Differentiating eqn. (13))} \\ &= (1-M)l(t)O(t)\left(\frac{\dot{l(t)}}{l(t)} + \frac{\dot{O(t)}}{O(t)}\right) < 0,\end{aligned}$$

where, $\dot{l(t)} < 0$ and $\frac{\dot{O(t)}}{O(t)} < 0$ along BGP.

Since, along BGP $\dot{H(t)} < 0$ and environment-friendly ABTC represents $\xi'(H(t)) < 0$, all cases become irrelevant except Case II. So we consider only case II, which depicts the fact that environmental degradation offsets or runs counter to economic growth.

Thus, along BGP, environmental degradation counters economic growth, although the economy remains progressive in nature with a minimal environmental degradational change along with environment-friendly ABTC.

3.9 Implications on Wage Inequalities

The simultaneous changes in technology and environmental quality affect income distribution through ability-differentiation and educational attainment. To show these effects, we first consider the comparative dynamics in an ABTC framework. The dynamics of per unit efficiency level are given in (A.6), where returns to skills or per unit efficiency levels are assumed to be functions of technological change and environmental change, and there is an erosion effect for ordinary-ability individuals and unskilled individuals, while no such effects exists for high-ability individuals.

The two inequality indices can be defined: wage inequality within skilled workers, denoted by Γ^s and wage inequality between skilled and unskilled workers, denoted by $\Gamma^{s/u}$, and these two inequality indices are determined as:

$$\begin{aligned}\Gamma^s &= \frac{N(t)^{se}.W(t)^{se}}{N(t)^{so}.W(t)^{so}} \\ &= \frac{h(t)}{l(t)}.\frac{M}{1-M}\left[\frac{\frac{\alpha}{1-\alpha}(1-\tau(t))+1}{\frac{\alpha}{1-\alpha}(1-\tau(t))-\frac{h(t)}{l(t)}\frac{M}{1-M}}\right],\end{aligned}$$

and

$$\begin{aligned}\Gamma^{s/u} &= \frac{W\bar{(t)}^s}{W\bar{(t)}^u} \\ &= \frac{\alpha}{1-\alpha}\left[\frac{1+M\left(\frac{h(t)}{l(t)}-1\right)}{\frac{\alpha}{1-\alpha}(1-\tau(t))-M\left(\frac{h(t)}{l(t)}-1\right)}\right],\end{aligned}$$

where $W\bar{(t)}^s$ & $W\bar{(t)}^u$ are respectively the average income levels of skilled and unskilled workers[11], which are functions of ability-differentiation $\left[i.e., \left(\frac{h(t)}{l(t)}\right)\right]$ due to technical change or environmental change or both and the time spent for educational attainment $(i.e., \tau(t))$.

Differentiating both Γ^s and $\Gamma^{s/u}$ with respect to both h(t)/l(t) and $\tau(t)$ we get respectively,

$$\frac{\partial \Gamma^s}{\partial\left(\frac{h(t)}{l(t)}\right)} = \frac{\frac{M}{1-M}\frac{\alpha}{1-\alpha}(1-\tau(t))\left(\frac{\alpha}{1-\alpha}(1-\tau(t))+1\right)}{\left(\frac{\alpha}{1-\alpha}(1-\tau(t))-\frac{h(t)}{l(t)}\frac{M}{1-M}\right)^2} > 0\,, \tag{50}$$

and

$$\frac{\partial \Gamma^{s/u}}{\partial\left(\frac{h(t)}{l(t)}\right)} = \frac{\alpha}{1-\alpha}\frac{M\left(\frac{\alpha}{1-\alpha}(1-\tau(t))+1\right)}{\left[\frac{\alpha}{1-\alpha}(1-\tau(t))-M\left(\frac{h(t)}{l(t)}-1\right)\right]^2} > 0\,. \tag{51}$$

Again,

$$\frac{\partial \Gamma^s}{\partial \tau(t)} = \frac{M}{1-M}\frac{h(t)}{l(t)}\frac{\frac{\alpha}{1-\alpha}\left(1+\frac{h(t)}{l(t)}\frac{M}{1-M}\right)}{\left[\frac{\alpha}{1-\alpha}(1-\tau(t))-\frac{h(t)}{l(t)}\frac{M}{1-M}\right]^2} > 0\,, \tag{52}$$

and

$$\frac{\partial \Gamma^{s/u}}{\partial \tau(t)} = \left(\frac{\alpha}{1-\alpha}\right)^2\frac{1+M\left(\frac{h(t)}{l(t)}-1\right)}{\left[\frac{\alpha}{1-\alpha}(1-\tau(t))-M\left(\frac{h(t)}{l(t)}-1\right)\right]^2} > 0\,. \tag{53}$$

[11] Average income levels of workers is defined as the total income (in efficiency units) of workers divided by the size of the work force.

Thus, both within-group and between-group inequalities increase due to an increase in ability-differentiation as well as educational attainment.

Hence, the comparative dynamics shows that both within-group and between-group inequalities are increasing over time with an increase in ability-differentiation as well as with an increase in time spent on educational attainment. Although high-ability and educated ordinary-ability workers are acquiring the same level of education, increasing educational attainment raises the per unit efficiency levels of high-ability workers more than the per unit efficiency levels of educated ordinary-ability workers due to the inherent ability-differentiation. As a result, within-group inequality rises. In comparison, as ordinary-ability individuals are acquiring more and more education over time and unskilled workers are not acquiring education at all, there arises a prominant increasing per unit efficiency levels gap between educated ordinary-ability individuals and unskilled individuals, which in turn raises the between-group inequality.

Simultaneously, any technological improvement or environmental quality change affects economic welfare due to an increase in both within and between inequalities. These effects on economic welfare can be determined by comparative dynamic analysis along the balanced growth path of the economy. As the balanced growth path of the economy given in eqn. (32) is a function of only ability differentiation, i.e., $\left(\frac{h(t)}{l(t)}\right)$ and not of the time spent on education, i.e., $\tau(t)$, we get that:

$$\frac{\partial\left(\frac{\dot{n(t)}}{n(t)}\right)}{\partial\Gamma^{s}} = \left[\frac{\partial\left(\frac{\dot{n(t)}}{n(t)}\right)}{\partial\left(\frac{h(t)}{l(t)}\right)}\right]\left[\frac{\partial\left(\frac{h(t)}{l(t)}\right)}{\partial\Gamma^{s}}\right] < 0\,, \tag{54}$$

and

$$\frac{\partial\left(\frac{\dot{n(t)}}{n(t)}\right)}{\partial\Gamma^{s/u}} = \left[\frac{\partial\left(\frac{\dot{n(t)}}{n(t)}\right)}{\partial\left(\frac{h(t)}{l(t)}\right)}\right]\left[\frac{\partial\left(\frac{h(t)}{l(t)}\right)}{\partial\Gamma^{s/u}}\right] < 0\,, \tag{55}$$

since,

$$\frac{\partial\left(\frac{\dot{n(t)}}{n(t)}\right)}{\partial\left(\frac{h(t)}{l(t)}\right)} = \frac{M(1-M)\left(\frac{\dot{l(t)}}{l(t)}\right)}{\left(\frac{h(t)}{l(t)}.M+(1-M)\right)^{2}} < 0\,.$$

Thus, both within and between inequalities distort economic welfare mostly through the channel of individual ability-differentiation, and not through educational attainment level.

Thus, the incorporation of environmental dimension in growth theory creates a trade-off between economic growth and environmental degradation, mainly environmental degradation off sets economic growth. These simultaneous effects of economic growth through technical change and environmental quality change have important implications on individuals' per unit efficiency levels or abilities. As a result, there exist a upward pressure on both within-group and between-group inequalities due to ability-differentiation as well as educational attainment. Further, both within-group and between-group inequalities distort economic growth through ability-differentiation, as ability-differentiation has a negative effect on economic growth. With these key findings from our analytical model, we proceed towards empirical validation of these results in the next section.

4 Empirical Analysis

4.1 Data and Methodology

In this section, we attempt to validate the findings of the theoretical analysis by empirically finding evidence of both DTC and ABTC, with key focus on ABTC with environmental constraints. For testing the effect of environmental degradation, we utilize air pollution indicators, namely, PM2.5 air pollution ($\mu g/m^3$) [12], denoted as EPM, CO_2 emission (kt) [13], denoted as ECO_2, environmental vulnerability index [14], denoted as EVul, and pollution index [15], denoted as PI. Further, GDP growth (annual %) [16] is used as an indicator of economic welfare, gross fixed capital formation (% of GDP) [17], denoted as GFC is used as an indicator of investment, while within-group[18] and between-group[19] educational attainment ratios, denoted as EAR_w and EAR_b respectively are utilized as indicators of time spent on education. Further, estimated within-group and between-group inequalities, denoted as INE_w and INE_b respectively are derived from efficiency wages (per worker) of unskilled, ordinary-skilled and high-skilled group of

[12]Data for PM2.5 air pollution, population exposed to levels exceeding WHO guideline value (percent of total) is collected from World Bank Databank.

[13]Data for CO_2 emissions is collected from World Bank Databank.

[14] Environmental Vulnerability Index is collected from ND-GAIN, i.e., Notre Dame Global Adaptation Initiative (organized by Climate Change Adaptation Program of the University of Notre Dame's Environmental Change initiative, i.e., ND-ECI).

[15]Pollution Index is collected from NUMBEO (organized by BBC, TIME, Forbes, Business Insider, Financial Times, Investopedia, SFGate, The New York Times, The Economist, The Week, The Sydney Morning Herald, The Age, The Independent, the guardian, The Telegraph, ABC, China Daily, People's Daily, Fox News, Wired, USA Today, The Vancouver Sun, The Washington Post).

[16]Data for GDP growth is collected from World Bank Databank.

[17]Data for gross fixed capital formation is collected from World Bank Databank.

[18]Within-group educational attainment ratio is calculated as the ratio of tertiary to secondary educational attainment.

[19]Between-group educational attainment ratio is calculated as addition of tertiary and secondary to primary educational attainment.

workers by using the data for labour force with different educational levels; primary, secondary and tertiary (% of total) [20], labour productivity calculated as output per worker (GDP constant 2011 $ in PPP) [21] and labour income (as a share of GDP) [22].

We examine the simultaneous effects of technological progress, i.e., economic growth and environmental degradation on income inequalities through education by utilizing Panel Corrected Standard Error (PCSE) model due to its better estimation procedure (see Beck and Katz (1995)). Next, the effects of environmental degradation and income inequalities, working through both education and individual ability differentiation, on economic welfare across 62 countries over the time period 1995-2015 are estimated. Finally, we present the convergence or divergence results for 23 developing countries as a group with respect to 39 developed countries over time by defining a dummy variable (d). The dummy variable d takes value one for developed countries and zero for developing countries, i.e.,

$$\begin{aligned} d &= 0, \qquad \forall \qquad \text{developing countries} \\ &= 1, \qquad \forall \qquad \text{developed countries} \end{aligned}$$

Here the characterization of the countries as developed or developing is made according to the World Bank Country and Lending Groups. The effects of environmental degradation and income inequalities, working through education and ability differentiation on economic welfare, are captured by interactions of environmental degradation and income inequalities with both educational attainment ratios (within and between) and ability-differentiations (within and between), predicted as the spatial error terms from the inequality (within and between) regressions individually. These interaction terms are the most significant feature of this study, as there is known significant effect of environmental change on human health (see Haines and Corvalan (2006), McMichael and Hales (2006), Bosello and Tol (2006)). Thus, affecting human efficiency indirectly, environmental change or air pollution is found to impact educational outcomes (see Miller and Vela (2013)).

We calculate income inequalities by using the above mentioned variables as,

[20] Data for labour force with primary, secondary and tertiary education (percent of total) to calculate labour productivity with respect to educational attainment are collected from World Bank databank. Also, total population (number of person) and emplyment to population ratio (% of total, modeled ILO estimate), to calculate total employment and educational attainment are collected from World Bank Databank.

[21] Data for labour productivity, to calculate income inequalities is collected from International Labour Organization (ILO).

[22] Dat for labour income, to calculate income inequalities is collected from International Labour Organization (ILO) for which dat for GDP (constant 2011 international dollars in PPP), to calculate labour income or wage is collected from World Bank databank.

Within-group inequality = $\frac{\text{per unit efficiency wage of high-skilled workers}}{\text{per unit efficiency wage of ordinary-skilled workers}}$

and, Between-group inequality = $\frac{\text{per unit efficiency wage of skilled workers}}{\text{per unit efficiency wage of unskilled workers}}$

where, per unit efficiency wages are determined as,

Per unit efficiency wage of high-skilled workers = labour productivity * $\frac{\text{total employment}}{\text{labour force with tertiary education}}$ * labour income or wage,

Per unit efficiency wage of ordinary-skilled workers = labour productivity * $\frac{\text{total employment}}{\text{labour force with secondary education}}$ * labour income or wage,

Per unit efficiency wage of unskilled workers = labour productivity * $\frac{\text{total employment}}{\text{labour force with primary education}}$ * labour income or wage.

From the analytical model we can see that, a rise or decline in inequalities are due to both educational attainment and ability-differentiation. We define educational attainment ratios for within and between groups so that by regressing inequalities on economic growth, all environmental variables, educational attainment ratios and interactions of variables with educational attainment ratios, ability-differentiations for within and between groups can be determined by using the prediction procedure of unobserved errors terms. Now, we define educational attainment ratios as,

Educational attainment ratio for within-group = $\frac{\text{educational attainment for high-skilled workers}}{\text{educational attainment for ordinary-skilled workers}}$

and, Educational attainment ratio for between-group = $\frac{\text{educational attainment for skilled workers}}{\text{educational attainment for unskilled workers}}$

where, educational attainment for different skilled workers are determined as,

Educational attainment for high-skilled workers = (total educational attainment at least short cycle tertiary[23] + total educational attainment at least post-secondary) * (total population),

Educational attainment for ordinary-skilled workers = (total educational attainment at least upper secondary + total educational attainment at least lower secondary) * (total population),

Educational attainment for unskilled workers = (total educational attainment at least primary) * (total population).

We considered that high-skilled workers acquire highest education (at least completed secondary), ordinary-skilled acquire education lower than high-skilled (secondary) and unskilled workers have minimum level of primary education. One can consider a higher level of education as educational attainment for high-skilled workers than what we considered, as there are higher levels of education than short cycle tertiary. However, we consider upto short cycle tertiary level of education so that there will not be so large

[23]Short cycle tertiary educational attainment indicates acquiring tertiary level of education for a short time period. It is not so high level of tertiary educational attainment.

gap between educational levels of high-skilled workers and ordinary-skilled workers and the unobserved ability can be captured easily. For such a higher level of education than short cycle tertiary education, it may possible that both educational-skill and ability-skill become inextricably linked.

The methods used in this study is provided step-wise as follows:

1. Decision making about one-way or two-way error component regression model depending on the unobservable factor, which may occur spatially or over time.

2. Check stationarity of all variables by using two unit-root test, namely, Levin-Lin-Chu test and Harris-Tzavalis test.

3. Regress economic growth, all environmental degradation variables, educational attainment ratios and the interactions of educational attainment ratios with economic growth and all environmental degradation variables on income inequalities by using both panel fixed effect model and panel random effect model.

4. Run the Hausman test to determine which is a better specification- fixed effect or random effect for the dataset.

5. Check for contemporaneous correlation, heteroscedasticity and auto-correlation problems by using the Friedman's test, Wooldridge test and Wald's test respectively.

6. Estimate income inequalities by Panel Corrected Standard Error model.

7. Calculate the predicted spatial error term using post-estimation procedure of panel fixed/ random effect model depending on which is more suitable which would yield the unobserved ability differentiation across countries in the form of the error terms.

8. Regress all environmental degradation variables, income inequalities and their interaction with educational attainment ratios and ability differentiation as predicted above, along with country dummy by using panel fixed/ random effect models.

9. Repeat steps no. 4, 5, and 6 for the above regression mentioned in step no. 8.

10. Repeat step no. 8 by using PCSE model for developed and developing countries individually by defining the value of the dummy variable (d) as 1 for developed and 0 for developing respectively.

11. Predict the value of the dependent variable, i.e., economic welfare for developed and developing countries respectively.

12. Trace the convergence or divergence paths of developing countries with respect to the developed countries by a graph.

4.2 Empirical Results

About the decision making of one-way or two-way error component regression model depending on the unobservable factor, which may occur spatially or over time; most of the panel data applications utilize a one-way error component model where the only unobservable disturbance factor is the individual effect. In our model also, the individual effects, i.e., ability-differentiation are unobservable and the time effects, i.e., technological improvement are observable through economic growth over time. Thus, in our estimation we use the one-way error component regression model due to the only unovseravble factor is ability-differentiation across individuals. After that, we proceed with the stationary check of all variables across countries over time.

4.2.1 Unit-Root Results

In this section, the results of both the Levin-Lin-Chu (LLC) and the Harris-Tzavalis (HT) unit-root tests are presented. The null hypothesis for both the unit-root test is that panel contains unit-roots. For HT test, we make an adjustment for time T for small sample and for LLC test, the optimal lag is included according to AIC (Akaike Information Criterion). Here unit-root test are performed in levels and the first-difference of variables, wherever needed. The unit-root test results are shown in Table 1. Trends are also included in unit-root tests for some variables those are showing some trend over the time period. From the table one can see that,

- In the unit-root tests, trends are considered for the variables EVul, ECO_2, EPM, INE_w in both LLC and HT tests, and for the variables INE_b, EAR_w, EAR_b in only HT test.

- Welfare, GFC, EVul, INE_b, EAR_w, EAR_b are stationary, i.e., in I(0) or level at both 1% and 5% level of significance according to both LLC and HT tests, as the p-values are less than 0.01 and 0.05 respectively.

Table 1: Unit-Root Results

Variables	Tests	Statistic	p-values	Remarks
Welfare	LLC	-16.5098	0.0000	Stationary
	HT	0.3402	0.0000	Stationary
GFC	LLC	-7.5228	0.0000	Stationary
	HT	0.7726	0.0000	Stationary
EVul	LLC	-4.8226	0.0000	Stationary
	HT	0.5644	0.0002	Stationary
ECO_2	LLC	-3.3415	0.0004	Stationary
	HT	0.7326	0.9971	Non-stationary
EPM	LLC	0.7041	0.7593	Non-stationary
	HT	0.9521	1.0000	Non-stationary
PI	LLC	-5.2492	0.0000	Stationary
	HT	0.9756	1.0000	Non-stationary
INE_w	LLC	10.7686	1.0000	Non-stationary
	HT	0.4813	0.0000	Stationary
INE_b	LLC	-12.0335	0.0000	Stationary
	HT	0.0318	0.0000	Stationary
EAR_w	LLC	-8.6147	0.0000	Stationary
	HT	0.0373	0.0000	Stationary
EAR_b	LLC	-7.4858	0.0000	Stationary
	HT	0.1482	0.0000	Stationary
$GECO_2$	LLC			
	HT	0.0173	0.0000	Stationary
GEPM	LLC	-6.4554	0.0000	Stationary
	HT	0.6727	0.0000	Stationary

- EPM is non-stationary at both 1% and 5% level of significance according to both LLC and HT tests, as the p-values are greater than 0.01 and 0.05 respectively. EPM is in I(1).

- ECO_2 and PI are stationary at both 1% and 5% level of significance according to only LLC test. These two variables are non-stationary according to HT test, as the p-values are greater than 0.01 and 0.05 for HT test.

- INE_w is stationary at both 1% and 5% level of significance according to HT test, but non-stationary as per LLC test since the p-values are greater than 0.01 and 0.05.

The HT unit-root test is the most appropriate unit-root test for our panel dataset since our data contain fewer time periods and more cross-sectional units. Thus, we consider INE_w as a stationary variable and ECO_2 as a non-stationary variable. On the contrary, we consider PI as a stationary variable[24], as per the LLC test result since PI is an index. Again for ECO_2, the LLC test shows stationary and the HT test shows non-stationary. So, we consider both the results and include both ECO_2 and $GECO_2$, i.e., the first difference of ECO_2 in our model estimation.

4.2.2 Results of Inequality Regressions

Here, the specific form of estimated models are:

$$\begin{aligned} INE_w = a_1 + b_1.Welfare + b_2.WEAR_b + c_1.EVul. \\ +c_2.EVulEAR_b + d_1.GEPM + d_2.GEPMEAR_b \\ +e_1.ECO_2 + e_2.ECO_2EAR_w + e_3.ECO_2EAR_b \\ +f_1.GECO_2 + g_1.PI + g_2.PIEAR_b \\ +h_1.EAR_w + h_2.EAR_b + u^s_{it}, \end{aligned} \tag{56}$$

[24]Although we check the estimation procedure by considering PI as non-stationary variable. The first difference of PI, i.e., GPI is again coming as non-stationary according to HT test, i.e., PI is in I(2) and thus we take the difference of first difference of PI and that becomes stationary. We continue the estimation procedure with difference of the first difference of PI variable, i.e., G^2PI, but the results are not significant. Thus, we exclude that variable from our estimation procedure.

and,

$$\begin{aligned} INE_b = a_2 + b_1.Welfare + b_2.WEAR_w + c_1.EVul. \\ +c_2.VulEAR_b + d_1.GEPM + d_2.GEPMEAR_b \\ +e_1.ECO_2 + e_2.ECO_2EAR_w + e_3.ECO_2EAR_b + f_1.GECO_2 \\ +f_2.GECO_2EARw + f_3.GECO_2EAR_b + g_1.PI \\ +h_1.EAR_w + h_2.EAR_b + u_{it}^{s/u}. \end{aligned} \tag{57}$$

For both the within-group and between-group inequality regression specified above, we test the Hausman

Table 2: Fixed vs. Random Effect for Inequality Regressions

Inequality	Prob>chi^2	Remarks
INE_w	0.0333	Random Effect
INE_b	0.0165	Random Effect

specification tests, shown in Table 2 and different tests for biasedness in estimates due to the presence of contemporaneous correlation or cross-sectional dependence, auto-correlation, heteroscedasticity, multi-collinearity etc. So we need to check for the presence or absence of these problems, shown in Table 3. Table 2 depicts that, for both within and between inequality regressions, the Prob>chi^2 value is greater than 0.01. Thus, we should accept the null hypothesis of random effect over fixed effect and hence, panel random effect model is estimated for inequality estimation and Table 3 says that, for both within and between inequality regressions, the Prob values are greater than 0.01 for Friedman's test and also, the Prob>F value is greater than 0.01 for Wooldridge's test. Thus, we should accept the null hypotheses of no contemporaneous correlation and no auto-correlation respectively at 1% level of significance.

Table 3: Presence of Different Problems In Inequality Regressions

Inequality	Prob. of Friedman Test	Prob.>F of Wooldridge Test
INE_w	0.7310	0.0830
INE_b	0.9986	0.6123
Remarks	No contemporaneous correlation	no auto-correlation

Although there do not exist problems of contemporaneous correlation and auto-correlation in our model, there may have others like, heteroscedasticity[25], sample selection bais, multicollinearity (as environmental vulnerability, emission of CO_2, growth of CO_2 emission, emission of PM2.5 are correlated with pollution index)[26] etc. To address these problems, we rely on the use of PCSE estimation first and then regress the significant independent variables from PCSE model on both the inequality variables respectively by using panel random effect model, so that we can get the predicted spatial error, i.e., u_i from both the inequality regressions. These spatial error terms actually represents the unobserved qualitative factors that may affect economic welfare. One of the most unobservable qualitative factor that is almost constant over time is the individual's inherent ability differentiation. In the estimation technique, the decision of being a significant independent variable depends on the z-value. If the z-value of any estimated independent variable is greater than or equali to 2, then one can say that, the independent variable affects the dependent variable significantly. By doing this, we can get the most likely predicted values of the spatial error terms by including the most significant independent variables.

The results of the within-group inequality estimation using PCSE is given in Table 4.

The above results can be interpreted as follows:

- Although welfare is not directly affecting within-group inequality significantly, it works significantly through between-group educational attainment as skilled workers are getting more education due to ABTC.

- Both within and between-group educational attainment ratios affect within-group inequality negatively and significantly. In presence of ABTC, due to discouragement effect, i.e., the negative incentive to acquire education for ordinary-ability workers as hiring high-ability workers is always profitable for firms, if the ordinary-ability workers don't acquire education and only high-ability workers do, in that case within-group educational attainment ratio increases. But, the net efficiency income decreases for high-ability workers as they have to spend some time from their work for attainment of education. As a result, within-group inequality decreases. Further, when more and more oridinary-ability workers acquire education for economic development, then the aggregate educational attainment level of skilled workers increases and thus it increases between-group

[25] There is no such test for heteroscedasticity with panel random effect models.

[26] We take environmental vulnerability, CO_2 emission and PM2.5 air pollution individually to show the short-term effects and pollution index to show long-term effects. Since pollution index is a combination of all environmental pollutants, there must have collinearity between pollution index and other environmental variables considered. Although there is multicollinearity problem, we estimate our models by including pollution index as a independent variable since it gives more appropriate results over the results of estimation by excluding pollution index.

Table 4: Within-Group Inequality Regression

Indept. Variables	Coeff.	z-value	P>$\|z\|$ value
Welfare	0.008978	0.38	0.701
EAR_w	-0.0059237	-3.18	0.001
EAR_b	-0.0104018	-5.03	0.000
$WEAR_b$	0.0003334	4.13	0.000
EVul.	9.828256	8.33	0.000
$EVulEAR_b$	0.0444827	5.15	0.000
GEPM	-0.1661468	-2.82	0.005
$GEPMEAR_b$	-0.0027731	-6.23	0.000
ECO_2	$-2.05e-07$	-3.16	0.002
ECO_2EAR_w	$2.48e-09$	3.04	0.002
ECO_2EAR_b	$-4.33e-09$	5.94	0.000
$GECO_2$	$-4.14e-06$	-2.41	0.016
PI	-0.0009058	-2.06	0.039
$PIEAR_b$	0.0000111	2.85	0.004
cons.	-0.6899724	-2.55	0.011

educational attainment ratio. As a result, the gap between net efficiency income between ordinary-ability and high-ability workers, within skilled work force declines. Thus, within-group inequality also declines.

- Environmental vulnerability directly as well as indirectly, through education, affects within-group inequality positively and significantly. More the environmental degradation, higher is the vulnerability to adopt any change, requiring faster innovation towards sustainable economic growth, which in turn raises within-group inequality.

- Growth of air pollution PM2.5, emissions of CO_2, growth of emissions of CO_2 and pollution index affect within-group inequality directly as well as indirectly, through education negatively and significantly. These negative effects may be due to the policies and institutions moving towards more eco-friendly ABTC, where a part of ABTC is lowering inequality through educational attainment.

- The emissions of CO_2 through within-group educational attainment and pollution index through between-group educational attainment impact within-group inequality positively and significantly, similar to the environmental vulnerability.

The results of between-group inequality estimation using PCSE is given in Table 5.

Table 5: Between-Group Inequality Regression

Indept. Variables	Coeff.	z-value	P>$\|z\|$ value
Welfare	-0.0496251	-1.58	0.115
EAR_w	-0.0192343	-1.62	0.106
EAR_b	0.005402	1.31	0.190
$WEAR_w$	0.001733	1.38	0.168
EVul.	15.24988	12.16	0.000
$EVulEAR_b$	-0.0241969	-1.39	0.165
GEPM	-0.1439125	-1.87	0.062
$GEPMEAR_b$	0.0009313	1.50	0.133
ECO_2	$-3.94e-07$	-3.37	0.001
ECO_2EAR_w	$2.10e-06$	1.79	0.073
ECO_2EAR_b	$2.38e-06$	3.20	0.001
$GECO_2$	$6.13e-06$	1.79	0.074
$GECO_2EAR_w$	$-5.73e-07$	-1.67	0.096
$GECO_2EAR_b$	$-2.60e-08$	-1.77	0.076
PI	0.0015598	2.80	0.005
cons.	-2.539973	-8.95	0.000

These results can be interpreted as follows:

- Although welfare declines between-group inequality as the coefficient is negative, it rises inequality through educational attainment due to ABTC. These effects are statistically insignificant as the z-values are less than 2.

- Within-group educational attainment ratio lowers between-group inequality whereas, between-group educational attainment ratio raises between-group inequality, though these effects are statistically insignificant. Such effects are may be due to the fact that, in presence of ABTC, due to discouragement effect, it may possible that ordinary-ability workers don't acquire education and thus within-group educational attainmnet ratio increases. As a result, the aggregate income of skilled workers decreases and thus, between-group inequality declines. Further, as more and more ordinary -ability workers acquire education, between-group educational attinment ratio increases with a simultaneous increase in the aggregate income level of skilled workers. As a result, between-group inequality rises.

- Environmental vulnerability, growth of CO_2 emissions and pollution index directly affect between-group inequality positively and significantly for EVul and PI, while for $GECO_2$ this effect is almost significant as it is closer to 2. Also, the growth of PM2.5 air pollution and CO_2 emissions through educational attainment raises between-group inequality significantly. Thus, with a rise in environmental degradation, between-group inequality rises.

- However, the growth of air pollution $PM2.5$ and CO_2 emission affects between-group inequality negatively and significantly. These negative impacts are may be due to the policies and institutional movement towards more eco-friendly ABTC, where a part of ABTC is lowering inequality. Similarly, environmental vulnerability and growth of CO_2 emissions through educational attainment lowers between-group inequality although these effects are statistically insignificant.

Thus, after estimating of the inequality regressions with PCSE model, as presented above, we estimate the inequality regressions by panel random effect model (including the same independent variables considered in PCSE method) to predict the most likely random error components u_w and u_b. After getting the predicted values of the spatial random error components from the two inequality regressions, we continue with the economic welfare regression in the next section.

4.2.3 Results of Welfare Regressions

The specific form of welfare regression model is estimated as:

$$\begin{aligned} Welfare_{it}^{W} = a_3 + b_1.GFC + c_1.EVulU_w + d_1.ECO_2 \\ +d_2.ECO_2U_w + d_3.ECO_2U_b + e_1.GECO_2 \\ +e_2.GECO_2EAR_w + e_3.GECO_2EAR_b + e_4.GECO_2U_b \\ +f_1.PIEAR_w + g_1.INE_w + g_2.INE_b + g_3.INEEAR_w \\ +g_4.INEEAR_b + g_5.INEU_w + g_6.INEU_b + h_1.d + u_{it}^{1}, \end{aligned} \tag{58}$$

Similarly done before, we perform Hausman specification test, shown in Table 6 and different tests for biasness in estimates, shown in Table 7. Table 6 shows that, the Prob$>$$chi^2$ value is less than 0.01.

Thus, we cannot accept the null hypothesis of random effect over fixed effect and hence, a panel fixed effect model has to be performed for further welfare estimation and Table 7 depicts that, the Prob. value for Friedman's test is less than 0.01, the Prob>F value for Wooldridge's test is less than 0.01 and also, the Prob$>chi^2$ value for Wald's test is less than 0.01. Thus, we cannot accept the null hypotheses of no contemporaneous correlation, no-auto-correlation and homoscedasticity at 1% level of significance. Thus, due to the presence of all of these problems, we continue the estimation of our welfare regression by using PCSE model for its better capability to produce more reliable standard errors than other estimation procedures.

Table 6: Fixed vs. Random Effect for Welfare Regression

Economic Welfare	Prob$>chi^2$	Remarks
Welfare	0.0000	Fixed Effect

Table 7: Presence of Different Problems In Economic Welfare Regression

Economic Welfare	Prob. of Friedman Test	Prob.>F of Wooldridge Test	Prob.$>chi^2$ of Wald Test
Welfare	0.0000	0.0000	0.0000
Remarks	Contemp. correlation	Auto-correlation	Heteroscedasticity

The results using PCSE for the whole economy is given in Table 8. It can be interpreted as follows:

- GFC has a positive significant effect on economic welfare. Thus, higher the investment in the economy higher will be the economic welfare.

- Environmental vulnerability through within-group ability-differentiation lowers economic welfare significantly. From Table4 it has been seen that, environmental vulnerability directly as well as indirectly increases inequality. So one can say that, as inequality rises, economic welfare declines. Thus, rising environmental degradation through ability-differentiation lowers economic welfare.

- Emissions of CO_2, directly as well as indirectly, through between-group ability-differentiation, affect economic welfare negatively and significantly. This effect may be due to the fact that, between-group ability-differentiation cannot be captured easily, as in both the skilled and unskilled labour force, ordinary-ability workers exist simultaneously. However, CO_2 emissions through within-group ability-differentiation improve economic welfare. Such effect may be due to the presence

Table 8: Welfare Regression For Whole Economy

Indept. Variables	Coeff.	z-value	P>$\|z\|$ value
GFC	0.2106642	4.75	0.000
$EVulU_w$	-1.017744	-3.90	0.000
ECO_2	$-1.65e-06$	-5.52	0.000
ECO_2U_w	$4.63e-07$	3.37	0.001
ECO_2U_b	$-9.13e-07$	-5.44	0.000
$GECO_2$	0.0000573	6.50	0.000
$GECO_2EAR_w$	$-3.16e-06$	-3.96	0.000
$GECO_2EAR_b$	$-6.41e-08$	-2.50	0.012
$GECO_2U_b$	0.0000157	3.68	0.000
$PIEAR_w$	0.0001072	1.71	0.088
INE_w	0.1071753	1.34	0.181
INE_b	-0.1189177	-1.74	0.082
$INEEAR_w$	0.0035276	1.00	0.317
$INEEAR_b$	0.000441	1.56	0.119
$INEU_w$	0.0131399	2.18	0.029
$INEU_b$	0.014455	1.27	0.204
d	-1.203166	-3.53	0.000
cons.	-0.5589357	-0.50	0.615

of ABTC, as within-group ability-differentiation, i.e., ability-differentiation between high-ability and ordinary-ability workers can be captured easily and aslo high-ability workers can cope quickly with any change, high-ability workers can handle the situation of increasing CO_2 emission quickly and thus increase economic welfare.

- Growth of CO_2 emissions directly as well as indirectly, through between-group ability-differentiation, significantly improves economic welfare. Similarly, pollution index through educational attainment has an almost significant (as the z-value is closer to 2) and positive effect on welfare. However, the growth of CO_2 through educational attainment significantly reduces economic welfare whcih is a natural case. The positive effects may be due to the fact that, in the long-run between-group ability-differentiation can be captured over time and then the ordinary-ability educated workers along with high-ability workers can manage the situation of increasing growth of CO_2 emission as well as increasing overall pollution level (captured by pollution index). This helps to increase economic welfare through the movement of the economy towards eco-friendly ABTC.

- Within-group inequality has a positive and between-group inequality has negative effects on economic welfare, though these effects are statistically insignificant as the absolute z-values are less than 2. However, both within and between-group inequalities improve economic welfare through educational attainment and ability-differentiation due to the skill-biasedness of ABTC, where the effect working through within-group ability-differentiation is found to be significantly.

- The country specific dummy variable d has a significant negative effect on economic welfare. The dummy variable actually captures the effect of the movement of associated factor from $d = 1$ to $d = 0$, i.e., movement of the economy from developed to developing nations. Thus the negative effect shows that, moving from a developed to developing country affects economic welfare adversely.

Now, after estimating the welfare regression for the whole economy, i.e., for the full dataset of 62 countries, we divide the world into 23 developing countries and 39 developed countries and then estimate the welfare regressions separately. Next, we calculate the linear predictions individually for developing and developed countries by using post-estimation techniques. Then, demonstrate the possibility of convergence or divergence for the developing countries with respect to the developed countries graphically. The specific form of the model for developing countries is estimated as:

$$\begin{aligned} Welfare_{it}^{UD} = a_4 + b_1.GFC + c_1.EVulEAR_w + c_2.EVulU_w \\ +d_1.ECO_2 + d_2.ECO_2EAR_w + d_3.ECO_2U_w \\ +e_1.GECO_2 + e_2.GECO_2U_w + f_1.PIEAR_w + f_2.PIU_w \\ +f_3.PIU_b + g_1.INE_w + g_2.INE_b + g_3.INEEAR_w \\ +g_4.INEEAR_b + g_5.INWU_w + g_6.INEU_b + u_{it}^2, \end{aligned} \tag{59}$$

and the results of estimating economic welfare for the developing countries are given in Table 9.

The results for welfare estimation of developing countries can be interpreted as:

- GFC affects economic welfare positively and significantly, as is also true for the entire sample.

Table 9: Welfare Regression For Developing Economies

Indept. Variables	Coeff.	z-value	P>$\|z\|$ value
GFC	0.2071168	3.43	0.001
$EVulEAR_w$	-0.5042884	-1.05	0.294
$EVulU_w$	-1.055716	-3.14	0.002
ECO_2	$-4.05e-06$	-3.08	0.002
ECO_2EAR_w	$-2.21e-06$	-3.22	0.001
ECO_2U_w	$-2.36e-06$	-3.02	0.002
$GECO_2$	0.0000746	4.94	0.000
$GECO_2U_w$	0.0000251	2.94	0.003
$PIEAR_w$	0.0026988	2.19	0.028
PIU_w	0.0016891	2.12	0.034
PIU_b	-0.0007308	-1.76	0.079
INE_w	0.0847156	0.81	0.419
INE_b	-0.3200832	-3.49	0.000
$INEEAR_w$	-0.0003024	-0.00	0.996
$INEEAR_b$	-0.0015103	-1.46	0.144
$INEU_w$	0.0159107	1.87	0.061
$INEU_b$	0.0624211	3.56	0.000
cons.	0.0815816	0.05	0.957

- Emissions of CO_2 directly as well as indirectly, through educational attainment and ability-differentiation significantly distort economic welfare due to more pollution. Similarly, environmental vulnerability through within-group educational attainment and ability-differentiation and pollution index through between-group ability-differentiation affect welfare negatively, where the effect of environmental vulnerability through ability-differentiation only is found to be statistically significant.

- Growth of CO_2 emissions has significant positive direct and indirect effect on economic welfare, where the latter works through ability-differentiation. Again, pollution index affects economic welfare positively, working through within-group educational attainment and ability-differentiation, may be due to the movement of the economy towards eco-friendly ABTC, as explained in Table8.

- Within-group inequality improves welfare for the developing countries, whereas between-group inequality lowers it significantly.

- Both within and between-group inequalities, through educational attainment, affect the welfare of developing countries negatively. However, both the inequalities improves economic welfare of the developing countries through ability-differentiation due to ABTC.

Next, the specific form of model of economic welfare for developed countries is estimated as:

$$\begin{aligned} Welfare_{it}^{D} &= a_5 + b_1.GFC + c_1.EVulEAR_w + c_2.EVulU_w \\ &+ d_1.ECO_2 + d_2.ECO_2U_w + d_3.ECO_2U_b \\ &+ e_1.GECO_2 + e_2.GECO_2U_b + f_1.PI + g_1.INE_w \\ + g_2.INE_b + g_3.INEEAR_w + g_4.INEEAR_b &+ g_5.INEU_w + g_6.INEU_b + u_{it}^{3}, \end{aligned} \tag{60}$$

and the results of welfare estimation for developed economies are given in Table 10.

The empirical results for the developed country group can be interpreted as follows:

- GFC has significant positive effect on economic welfare for developed economies also, which is more generally true as well.

- Emissions of CO_2 directly as well as indirectly, operating through between-group ability-differentiation, affect the welfare of the developed economies negatively and significantly. Similarly, environmental vulnerability lowers economic welfare through within-group educational attainment and ability-differentiation significantly as increasing pollution reduces economic welfare.

- However, the growth of CO_2 emissions and pollution index directly improve economic welfare of the developed countries significantly. Also, CO_2 emissions, operating through within-group ability-differentiation, and the growth of CO_2 emissions, working through between-group ability-differentiation, affect economic welfare positively and significantly may be due to the movement of the economy towards eco-friendly ABTC.

- Both within and between-group inequalities promote welfare for the developed economies perhaps due to the innovation towards new technologies, though these effects are statistically insignificant as the z-values are less than 2.

Table 10: Welfare Regression For Developed Economies

Indept. Variables	Coeff.	z-value	P>$\|z\|$ value
GFC	0.2328869	3.95	0.000
$EVulEAR_w$	-0.3091126	-1.88	0.060
$EVulU_w$	-1.955493	-3.44	0.001
ECO_2	$-2.66e-06$	-4.69	0.000
ECO_2U_w	$1.32e-06$	3.72	0.000
ECO_2U_b	$-5.83e-07$	-3.03	0.002
$GECO_2$	0.0000316	6.97	0.000
$GECO_2U_b$	0.0000179	4.10	0.000
PI	0.0016863	1.80	0.073
INE_w	0.0778274	0.44	0.659
INE_b	0.1715276	1.47	0.142
$INEEAR_w$	0.0554837	2.04	0.042
$INEEAR_b$	0.0006939	2.70	0.007
$INEU_w$	-0.013629	-0.28	0.780
$INEU_b$	-0.0585257	-3.35	0.001
cons.	-2.677987	-1.94	0.053

- Inequality through educational attainment significantly improves the welfare of the developed economies due to ABTC. However, inequality through between-group ability-differentiation declines economic welfare significantly as higher between-group ability-differentiation leads to a higher distortion in income distribution.

Thus it has been seen that, the effects of CO_2 emission through within-group ability-differentiation and both within and between-group inequalities directly and indirectly through educational attainment ratios and ability-differentiation affect economic welfare of developing and developed countries differently. Due to the movement towards eco-friendly ABTC, high-ability workers can cope with any environmental change, like CO_2 emission quickly and increase economic welfare in developed countries compared to developing countries as there must be more number of high-ability workers in developed countries than in developing ones.

Again, for the inequality effects it has been seen from Tables9 and 10 that, within-group inequality does not matted as such due to its statistical insignificance, similar to the effect for the whole economy (see Table8). However, between-group inequality significantly affects economic welfare adversely for developing nations as it creates economic distortions with respect to distributional aspects. However, between-group inequality improves economic welfare for developed nations, which may be due to the faster technological improvement in developed nations, although this effect is statistically insignificant. Further, inequality through educational attainment and ability-differentiation respectively decreases and increases economic welfare for developing countries, whereas for developed countries it increases and decreases economic welfare respectively. These varied effects are may be due to the fact that, for developed countries what matters ultimately in the long-run is individual inherent ability. So any kind of inequality due to ability-differentiation is not good for them in the long-run as they already reached at some targeted level of economic developement. Whereas, inequality due to educational attainment captures the capability to cope with the short-run effects of technological improvements, which increase economic welfare as a result of technological improvement. However, for developing countries also ability being the main factor which matters ultimately in the long-run, any kind of inequality due to ability-differentiation is good for them in the long-run as they have to catch the targeted level of economic development at which developed countries are already there. Whereas, inequality due to any kind of difference in educational attainment is not good for developing countries, which leads to the need of an equal education for all within the economy for its development.

After estimating developing and developed economy individually, we make the linear prediction of the welfare of two economies. The overall predicted economic welfare for the developing and developed economies are shown by Figure 5 and Figure 6 respectively, given in Appendix A. Then, we present the convergence or divergence for the developing economy with respect to developed economy over the time period 1995-2015 in Figure 4. In Figure 4, the red triangles, connected by blue lines represent the linear predicted values of economic welfare of developing countries and the blue circles, connected by red lines represent the linear predicted values of economic welfare of developed countries.

As can be seen, over the time period 1995-2015, developing countries in general are found to almost converge to the developed countries due to eco-friendly ABTC through educational attainment and inherent ability-differentiation. Only one developing country is in very lower conditiodoes not demonstrate this. By comparing Figure 4 and Figure 5, we can see that this odd-one country is the 8th developing country, which is Kazakhstan in our sample. Some reasons for this economic backwardness that can be offered are poor labour market structure, lower capacity for investing more in R&D sectors, poor

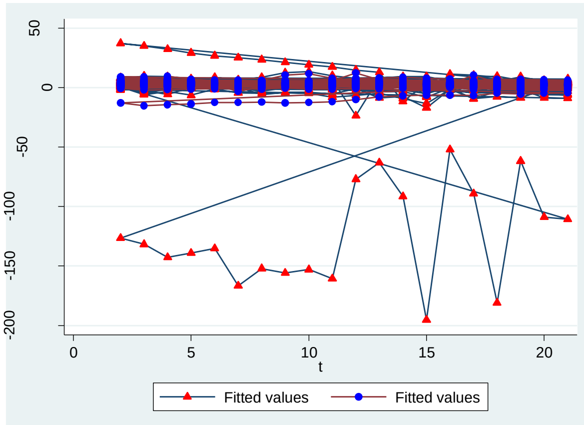

Figure 4: Convergence or Divergence of Economies over the Time Period 1995-2015

environmental conditions, which may not be supportive towards higher growth trajectory.

5 Conclusion

The present paper mainly focused on the idea of endogenous growth models with biased technical change where at first educational-differentiation and then ability-differentiation are the driving forces of economic growth. We discussed the concepts of within-group and between-group wage inequalities and the effects of biased technical change through educational-differentiation and ability-differentiation on both the inequalities. Simultaneously, we introduced the newly developed concept of directed technical change with environmental constraints. We next alluded to the simultaneous effects of ability-biased technical change (a part of skill-biased technical change) and environmental degradation (as a by-product of final production) on income inequalities. In equilibrium it has been seen that, individual's per unit efficiency level and time spent on education determines the size of educated ordinary-ability work force and hence, the balanced growth path of the economy is solely depending on the per unit efficiency levels of workers and its growth, where the growth path is progressive and converging in long-run with a decline in skilled labour force. Further it has been found that environmental degradation offsets economic growth, where change in skill supply declines due to both erosion effect and discouragement effect in ability-biased technical change and the chnage in environmental degradation is also declining with respect to skill supply due to environment-friendly ability-biased technical chnage. However, at constant level of environmental degradation also there is positive trade-off between economic growth and environmental degradation along with progressive economic growth. Finally both within and between-group wage inequalities are increasing due to ability-differentiation as well as educational aquisition, since a little more educational attainment may make an significant per unit efficiency gap and thus in turn an income gap also. Again, economic welfare decreases along the balanced growth path through mainly ability-differentiation, since both inequalities are increasing, which means more distortion of economic distribution and these ability-differentiation are mostly due to environmental quality change as environment degrades in a faster rate than technological progress in general. Also we tried to show the convergence or divergence for developing economies with respect to developed ones due to ability-biased technical change for 62 countries, among which 23 are devepoling countries and 39 are developed countries over the time period 1995-2015. Some environmental degradational indicators promote economic welfare due to the movement of the economy towards eco-friendly ABTC and others hinder economic welfare due to the usual reason, i.e., environmental degradation is not good for any country at all. Again, economic welfare decreases as a result of the distortion in economic distribution for only developed economies, whereas income inequalities improves economic welfare through ability-differentiation for developing countries, may be due to the fact that, developed countries already reached to a targeted level of economic development and developing countries have to catch the developed ones over time. Finally, we show that through out the period of time 1995-2015, developing countries are almost converging with respect to the developed countries, except Kazakhstan which has the lowest economic welfare as per the measure used by us.

A Appendix

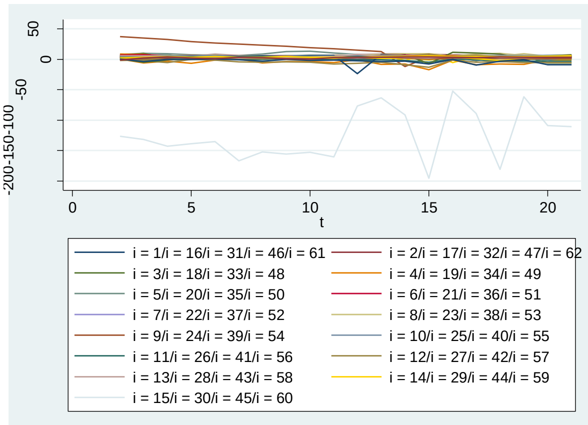

Figure 5: Overall Economic Welfare of All Developing Countries for the Time Period 1995-2015

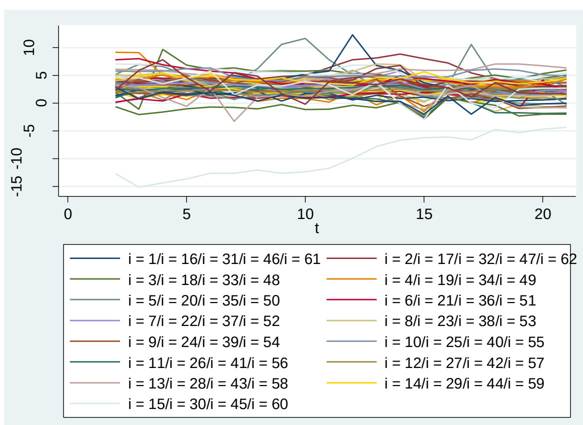

Figure 6: Overall Economic Welfare of All Developed Countries for the Time Period 1995-2015

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