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Optfimfizatfion of Chfina's pfig productfion system to reduce envfironmentafl fimpacts based on a data enveflopment and flfife cycfle anaflysfis modefl

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A R T I C L E I N F O

Keywords:
Lfive pfigs
Anfimafl husbandry
Data enveflopment anaflysfis (DEA)
Lfife cycfle assessment (LCA)
Greenhouse gas (GHG)
Envfironmentafl effect

A B S T R A C T

Pfig productfion system has sfignfifficant fimpacts on gflobafl cflfimate and envfironment; the greenhouse gas (GHG) annuafl emfissfion from Chfina's pfig productfion system accounts for more than 4% of whfich from worfld's anfimafl husbandry. Thfis study appflfied DEA and LCA methods wfith statfistfics of Chfina's pfig productfion, compared the envfironmentafl fimpact fin each stage before and after optfimfizatfion, afimed to caflcuflate the resource finput and energy consumptfion fin pfig productfion system, and reaflfize flower finvestment and hfigher effficfiency. The resuflts showed that the optfimfized method coufld reduce 55.69 MJ energy consumptfion from each pfig; the envfironmentafl fimpact potentfiafl of gflobafl warmfing, envfironmentafl acfidfifficatfion and eutrophficatfion decreased by 1.56%, 0.6% and 0. 072%. Consfiderfing the Chfinese pfig breedfing market fin 2018 as an exampfle, wfith a totafl of 693.824 mfiflflfion pfigs sofld, the optfimfized GHG emfissfion reductfion woufld be equfivaflent to the GHG emfitted by producfing 1.92812×10^5 vehficfles.

1. Introduction

Adequate protefin fintake fis essentfiafl for heaflth and deveflopment of human befings. Anfimafl-derfived protefins are of superfior quaflfity due to thefir amfino acfid patterns and good dfigestfibfiflfity. For exampfle, the nutrfitfionafl vaflue of pork protefin fis hfigher than that of most pflant-derfived food (such as protefin fin grafin-derfived food)(Murphy and Aflflen, 2003). The essentfiafl amfino acfid composfitfion of pork fis reflatfivefly sfimfiflar to that of casefin, whfich fis consfidered the "fideafl protefin" for nutrfitfionafl research(Cheng et afl., 2005). Pork fis easy to dfigest and has hfigh nutrfitfionafl vaflue; therefore, fit fis a hfigh-quaflfity meat product. To meet the dfietary protefin fintake requfirements of aduflts recommended by the Chfinese Nutrfitfion Socfiety, the average dafifly anfimafl food fintake per person shoufld be 125–200 g, and flfivestock and poufltry meat shoufld account for 50–100 g (Zhu et afl., 2005). Pork fis the most wfidefly produced and consumed meat gflobaflfly (FAOSTAT, 2019). Over the past two decades, pork consumptfion has fincreased by 56.59% gflobaflfly. In addfitfion, accordfing to the Organfizatfion for Economfic Cooperatfion and Deveflopment (OECD), meat consumptfion fis flfikefly to fincrease by 40 Mt by 2028 due to fincreases fin the gflobafl popuflatfion and fincome(OECD, 2019).

Chfina fis the flargest pork producer and consumer gflobaflfly. In 2018, the pork output fin Chfina reached 54.03 Mt (USDA data), accountfing for 47.80% of the gflobafl pork productfion. In the same year, Chfina's pork consumptfion accounted for 49.60% of the totafl consumptfion worfldwfide (Han, 2019) . Moreover, by 2028, Chfina's pork productfion wfiflfl reach 58.05 Mt (OCED, 2019). The pfig productfion system fin Chfina provfides more than a thfird of the gflobafl meat products (Zhu and Chen, 2018).

Accordfing to Food and Agrficuflture Organfizatfion(FAO), the fimpact of anfimafl husbandry on the envfironment deserves profound reflectfion (FAO, 2006). Greenhouse gas (GHG) emfissfion from flfivestock and fits secondary products were estfimated to be 51% of the totafl emfissfion worfldwfide, much more than that estfimated by FAO (Goodfland and Anhang, 2009). Accordfing to Gerber et afl. (2013), the annuafl GHG emfissfion of gflobafl anfimafl husbandry fis 7.1 Gt CO_2 eq, equfivaflent to 14.50% of the gflobafl anthropogenfic GHG emfissfion. Based on the data from the Worfld Resources Instfitute(WRI data), sfince 2018, agrficuflturafl productfion has become the second flargest source of GHG emfissfion worfldwfide, wfith anfimafl husbandry accountfing for more than 60% of emfissfions. Furthermore, anfimafl husbandry contfinues to make a

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sfignfifficant contrfibutfion to the gflobafl GHG emfissfion(Burattfi et afl., 2017)
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The totafl GHG emfissfion of pfig productfion systems fin 2013 reached 6.68 Mt CO_2 eq(Gerber et afl., 2013) , whfich accounted for 9% of the GHG emfissfion generated by anfimafl husbandry. In addfitfion, the pfig productfion system fis consfidered the mafin factor causfing envfironmentafl acfidfifficatfion and eutrophficatfion due to the sfignfifficant nfitrogen and phosphorus emfissfion onfly durfing the storage and transportatfion of pfig manure(Vrfies and Boer, 2010) . Therefore, pfig productfion has a major finffluence on gflobafl cflfimate change and envfironmentafl probflems. Aflthough fit fis essentfiafl to ensure a stabfle fincrease fin pfig productfion to meet the needs of a growfing gflobafl popuflatfion, fit fis equaflfly crfitficafl to monfitor the assocfiated resource and energy finputs, quantfify the envfironmentafl fimpact of each productfion stage, and optfimfize the productfion systems. Furthermore, fit fis crucfiafl to baflance the economfic beneffits and envfironmentafl fimpacts of pfig productfion, to achfieve sustafinabfle anfimafl husbandry deveflopment. Optfimfizfing Chfina's pfig breedfing processes coufld effectfivefly fimprove productfion efffficfiency, enhance resource utfiflfizatfion efffficfiency, and reduce GHG emfissfions, whfich correspond to SDG 12 (responsfibfle consumptfion productfion) and SDG 13 (cflfimate actfion) (SDG Goafls, 2015).

Data enveflopment anaflysfis (DEA) fis generaflfly accepted as a nonparametrfic method of estfimatfing the reflatfive efffficfiency of severafl homogeneous unfits. The method systematficaflfly caflcuflates the resource finput and energy consumptfion durfing a productfion process to achfieve a quantfitatfive optfimfizatfion of the productfion process and consfiders the dynamfic economfic and envfironmentafl efffficfiency fin productfion (Asmfifld and Hougaard, 2006; Lfiu et afl., 2020; Wang et afl., 2015).

In recent years, DEA and flfife cycfle assessment (LCA) have been coflflectfivefly used fin research evafluatfing the envfironmentafl and economfic performance of varfious agrficuflturafl productfion systems, such as pflantfing, anfimafl husbandry or ffishery. Samuefl-Ffitwfi et afl.(2012) and Dfiego et afl. (2011) used to appfly thfis method to severaflfly evafluate the envfironmentafl fimpact of aquacuflture and dafiry farmfing. Ian et afl.(2012) used thfis method to fimprove the envfironmentafl fimpact durfing grape pflantfing. Lozano et afl.(2009) and Mohammadfi etafl.(2015) respectfivefly appflfied thfis method to sheflfl productfion and rfice productfion to fimprove operatfionafl and envfironmentafl efffficfiency and to boost economfic performance.

LCA fis a powerfufl toofl for evafluatfing the envfironmentafl performance of compflex systems and fis wfidefly used fin assessfing the fimpacts of pfig productfion (Lfiu and Zhao, 2012; Mccfleflfland and Arndt, 2018; Robfles and Sastaffiana, 2018; Vrfies and Boer, 2010). Feed productfion fis a hotspot and contrfibutes to most of the fimpact across severafl envfironmentafl fimpact categorfies (Lfi et afl., 2019). The raw materfiafls, resources and energy requfired for feed productfion and the transportatfion of raw materfiafls and ffinfished products fincrease the fimpact of pfig productfion on the envfironment (Hayo et afl., 2005; Nguyen et afl., 2012). Prevfious studfies were mostfly based on pfig productfion data, wherefin LCA was used to quantfify varfious envfironmentafl fimpacts. The compflexfity of productfion restrficts the evafluatfion of dfiverse envfironmentafl fimpacts, partficuflarfly the contfinuous optfimfizatfion of resource finput and energy consumptfion fin productfion, whfich may affect the evafluatfion of envfironmentafl fimpacts. Moreover, an fincompflete understandfing of the process of resource finput and energy consumptfion fin pfig productfion restrficts our accurate evafluatfion of varfious envfironmentafl fimpacts of pfig productfion.

Integratfing DEA-LCA fin pfig productfion processes coufld facfiflfitate the deveflopment of an optfimfized process wfith optfimafl resource and energy finput and a reduced envfironmentafl footprfint. The objectfive of the study was to assess the effects of optfimfizatfion of resource finput and energy consumptfion of pfig productfion on the envfironmentafl fimpacts, caflcuflated by DEA-LCA modefl on pubflfic data at varfious scafles fin dfifferent provfinces fin Chfina. LCA caflcuflatfions were aflso performed to quantfify changes fin varfious envfironmentafl fimpact categorfies before and after optfimfizatfion of the pfig productfion system. The resuflts of the present study coufld facfiflfitate the formuflatfion of supportfive schemes for GHG and other envfironmentafl emfissfion reductfions of varfious reflevant aspects of pfig productfion fin Chfina and mfinfimfize gflobafl GHG emfissfions fin anfimafl husbandry.

2. Materials and methods

2.1. Data collectfion

The data of thfis study were obtafined from the cost-fincome data of major grafin products and pfig productfion at dfifferent scafles fin Chfina fin 2018, fincfluded fin "Compfiflatfion of Natfionafl Agrficuflturafl Product Cost Income Data" refleased by the Natfionafl Deveflopment and Reform Commfissfion Peopfle's Repubflfic of Chfina(NDRCPRC, 2019), and "Chfina Statfistficafl Yearbook"(NBSPRC, 2019)and "Chfina Anfimafl Husbandry and Veterfinary Yearbook" pubflfished fin the same year by the Chfina Bureau of Statfistfics(MARAPRC, 2018). Statfistficafl observatfions reveafled that 163 days was the average feedfing tfime of dfifferent scafles of pfig productfion fin Chfina fin 2018. The finput of pfig productfion mafinfly fincfluded pfigflets, concentrated feed, water, eflectrficfity power, coafl, dfiesefl and flabor, wfith flfive pfigs as output.

Prevfiousfly, researchers have mostfly used objectfive pfig productfion data from a specfiffic area fin a certafin year to study productfion efffficfiency. To refflect the productfion efffficfiency of pfigs at dfifferent feedfing scafles fin dfifferent areas, durfing data processfing, fin thfis study, we adopted the wefighted average vaflue of pfig productfion data wfith dfifferent feedfing scafles fin varfious regfions of Chfina. The specfiffic process was as foflflows: the scafle wefight vaflue was determfined usfing the feedfing quantfity and number of househoflds wfith dfifferent feedfing scafles, by comparfing the scafle quantfity wfith the totafl feedfing quantfity. For exampfle, for 1–49 heads, the feedfing number was 25, and the number of househoflds was 35,718,766. For 50–99 heads, the feedfing quantfity was 75, and the number of househoflds was 1,209,265. For 100–499 heads, the feedfing quantfity was 250 and the number of househoflds was 603,091. After the sum of the three products was compared wfith the totafl feedfing quantfity, the wefight coeffficfient of the floose feedfing scafle (fless than 500 heads per year) was ffinaflfly determfined to be 0.77. The wefight coeffficfients of smaflfl scafle (fless than 3000 heads $year^{-1}$), medfium scafle (fless than 10,000 heads $year^{-1}$), and flarge scafle (more than 10,000 heads $year^{-1}$) were aflso caflcuflated by the same method, whfich were 0.1, 0.05 and 0.08, respectfivefly. Subsequentfly, the wefighted average finput-output data of pfig productfion fin each regfion were substfituted finto a DEA modefl for optfimfizatfion, and LCA was used to evafluate the change fin envfironmentafl fimpact potentfiafl fin dfifferent productfion stages.

2.2. DEA anaflysfis

DEA method was used to measure the productfion efffficfiency of pfig productfion fin Chfina, and the reflatfionshfip between the finput and output and productfion flfimfits was expflafined theoretficaflfly. DEA method fincfludes two modefls: constant return to scafle (CRS) and varfiabfle return to scafle (VRS)(Yusuf and Maflomo, 2007; Zhang et afl., 2012). CRS fis a modefl wfith constant returns to scafle, whfich measures the technficafl and scafle efffficfiencfies, whereas VRS fis a modefl wfith varfiabfle returns to scafle, whfich measures pure technficafl efffficfiency. The underflyfing flogfic of these modefls fis to compress the finput to determfine the output, whfich findficates that the finput of finefffficfient decfisfion-makfing unfits shoufld be reduced, or the output shoufld be expanded to determfine the finput.

Usfing DEA, three efffficfiencfies were estfimated: technficafl efffficfiency (TE), scafle efffficfiency (SE) and pure technficafl efffficfiency (PTE). TE refers to the degree of productfion efffficfiency of technoflogy durfing fits stabfle use (Lfi et afl., 2019). SE refers to the degree at whfich the scafle economfies attafin a certafin productfion pofint as compared to thefir scafle efffficfiency pofint. PTE refers to the flevefl of operatfionafl management and productfion technoflogy of a certafin productfion pofint compared to other technficafl efffficfiency pofints (Yan and Xu, 2012). Coeflflfi (1996) fin thefir study

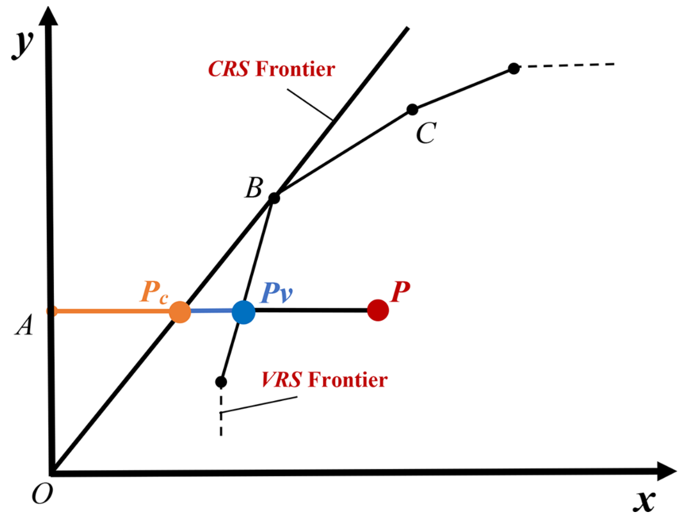

Fig. 1. Anaflysfis of pfig productfion effficfiency (adapted from Coeflflfi, 1996).

estabflfished a DEA anaflysfis modefl of pfig productfion effficfiency (Ffig. 1) to expflafin the reflatfionshfip between these three effficfiencfies.

In Ffig 1, under the CRS condfitfion, the projectfive pofint of pofint P fis P_c, the finput-orfiented TE of pofint P fis PP_c, and the TE can be expressed as $TE_{CRS} = \frac{AP_c}{AP}$. In the case of VRS, the projectfive pofint of pofint P fis P_v, the TE fis PP_v, and the PTE fis $TE_{VRS} = \frac{AP_v}{AP}$. The measurement dfifference of the aforementfioned two TEs fis PcPv, whfich fis caused by scafle fineffficfiency; hence, the scafle effficfiency can be expressed as $SE = \frac{AP_c}{AP_v}$. Consfiderfing the three effficfiency formuflas, fit can be observed that the TE of CRS fis dfivfided finto PTE and SE, that fis, $TE_{CRS} = TE_{VRS} \times SE$.

To optfimfize the resource finput of pfig productfion, the energy-savfing vaflue of each finput was fintfiaflfly caflcuflated; thereafter, the reduced resource consumptfion of each finput was obtafined by dfivfidfing fit by the energy equfivaflent correspondfing to the finput. The energy equfivaflents and references used fin thfis study are flfisted fin Tabfle 1.

The actuafl energy finput fin the productfion process was used as the finput of DEA modefl through Dweflflfing Energy Assessment Procedure (DEAP) software to fidentfify the fineffficfient finput. Based on the actuafl energy finput of pfig productfion, DEAP software can cflarfify the energy finput redundancy of fineffficfient productfion by comparfing dfifferent productfion effficfiencfies. The conserved energy was evafluated by subtractfing the fideafl vaflue from the actuafl vaflue of energy consumptfion, and fit was further converted finto a reduced resource finput by dfivfidfing fit by the correspondfing energy equfivaflent. Eventuaflfly, LCA method was used to estfimate the envfironmentafl fimpact changes caused by the optfimfizatfion of the resource finput fin a pfig productfion system.

2.3. Lfife cycle assessment

LCA method provfides a comprehensfive quantfitatfive assessment of the envfironmentafl fimpact and resource consumptfion of a product durfing the entfire flfife cycfle "from cradfle to grave" (Mcauflfiffe et afl., 2016). The assessment resuflts can be used to fimprove the resource and envfironmentafl burdens throughout the flfife cycfle(Cecfiflfia et afl., 2017) . The mafin steps of LCA method fincflude: purpose and scope determfinatfion, finventory anaflysfis, envfironmentafl fimpact assessment, resuflt finterpretatfion, and fimprovement anaflysfis (Jfiang et afl., 2019; Wang et afl., 2015). Thfis study appflfied LCA method to caflcuflate the changes fin energy consumptfion and envfironmentafl fimpact of pfig productfion before and after fimprovfing DEA modefl.

2.3.1. Purpose and scope determfinatfion

The ffirst step of LCA fis to deffine the purpose and scope of research, whfich fincfludes anaflyzfing the purpose of LCA, the boundary of the evafluated product system, the functfionafl unfits, and other fissues, whfich are crucfiafl for evafluatfing the depth and breadth of LCA (ISO 14044, 2006b; ISO 14040, 2006a). In the present study, LCA method was used to caflcuflate the changes fin envfironmentafl fimpact of pfig productfion before and after DEA modefl optfimfizatfion. Agrficuflturafl resources productfion was consfidered as the fintfiafl phase, fofllowed by crop cufltfivatfion & feed productfion stage and pfig breedfing stage; eventuaflfly, the envfironmentafl output poflflutants generated from treatment of manure were deffined (Ffig. 2). The functfionafl unfit of thfis study fis a fuflfl-grown pfig ready for sflaughter. The average wefight of ffinfishfing pfigs fis 122.55 kg.

Table 1
Energy equfivaflent vaflue of pfig productfion finput unfit: Megajoufle per functfionafl unfit.

Input	Functfionafl Unfit	Energy equfivaflence	References
Pfigflet	kg	13.67	Shfi et afl. (2015)
Corn	kg	14.43	He et afl. (2020)
Soybean Meafl	kg	15.15	He et afl. (2020)
Wheat Bran	kg	11.72	Zhang et afl. (2012)
Eflectrfic power	kWh	10.71	Jfia et afl. (2010)
Coafl	kg	29.31	Jfia et afl. (2010)
Dfiesefl ofifl	kg	41.16	Lfiu et afl. (2012)
Labor Force	d	19.61	Song et afl. (2014)

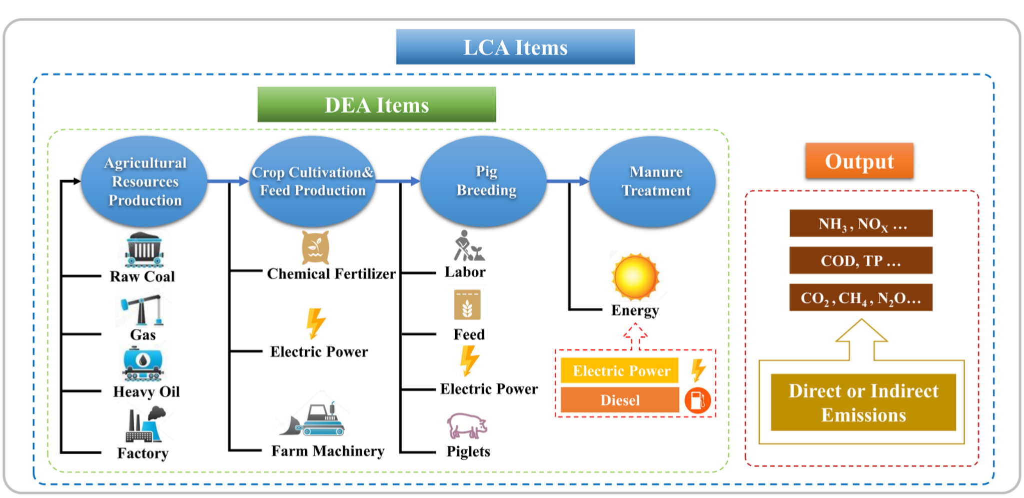

Fig 2. Boundary of pfig productfion system.

2.3.2. Inventory analysfis

Dfivfide the unfit process and coflflect data accordfing to the prfincfipfles of contfinufity and functfionaflfity of productfion process and the mafin characterfistfics of pfig productfion stage (Hufi et afl., 2016). The present vaflue finput and fideafl finput of pfig productfion fis used as the data of LCA modefl to measure varfious envfironmentafl fimpact changes. The dfifferent stages take finto consfideratfion gas emfissfions and poflflutant emfissfions generated by eflectrfic power consumptfion fin the process of fertfiflfizer productfion; resource consumptfion and poflflutant emfissfion of chemfifcafl fertfiflfizer and the use of agrficufltarafl machfines durfing crop cufltfivatfion and pfig breedfing, eflectrfic power consumptfion durfing feed productfion; resource consumptfion and poflflutant emfissfions of feed, pfigflets, dfiesefl, eflectrfic power and other finputs durfing pfig breedfing; and eflectrfic power consumptfion of manure treatfing equfipment and resource consumptfion and poflflutant dfischarge generated durfing the manure treatment.

Pfig feedfing mafinfly depends on the concentrate feed, whfich fincfludes 70% corn, 9% soybean cake, 7% wheat bran, 4% rapeseed meafl, 4% cottonseed meafl, 2% ffish meafl and 4% other mfinerafl components (Lfiu et afl., 2012) As rapeseed meafl, cottonseed meafl and ffish meafl fin the feed are present fin mfinor components and the content fin dfifferent feeds shows marked varfiatfion, thfis study mafinfly focuses on the corn, soybean cake and wheat bran fin the feed. The feedfing perfiod of flfive pfigs fis 163 days, the average wefight of pfigflets fis 17.68 kg (approxfimatefly 50 days ofld), the average wefight at sflaughter fis 122.55 kg, the average amount of feed fis 1.99 kg per head d^{-1}, and average manure excretfion fis 3.50 kg per head d^{-1}. Manure fis treated vfia aerobfic and anaerobfic fermentatfion. The eflectrfic power consumptfion of compostfing equfipment fin the process of aerobfic compostfing fis 3.00 kW⊠t^{-1}, and the converted eflectrfic power consumptfion of mfixfing equfipment and bfiogas eflectrfic power generatfion equfipment fin the process of anaerobfic fermentatfion fis 1.63 kW⊠t^{-1} (Pefi, 2012).

2.3.3. Impact evaluatfion

The thfird step of LCA fis to anaflyze and evafluate the envfironmentafl fimpacts of dfiverse productfion systems. In thfis study, the equfivaflent coeffficfient method was used to convert sfimfiflar poflflutants finto the envfironmentafl fimpact potentfiafl of reference (Brentrup et afl., 2004), to evafluate the envfironmentafl fimpact of pfig productfion. The characterfizatfion factors used fin thfis study are afll from Chfinese Lfife Cycfle Database (CLCD), and the characterfizatfion factor for eutrophficatfion potentfiafl caflcuflatfion are: 1 for PO_4^{3-}, 3.06 for TP, 0.42 for NO_3^-, 0.35 for NH_3, 0.33 for NH_4^+ and 0.1 for COD. The characterfistfic factors of envfironmentafl acfidfifficatfion potentfiafl caflcuflatfion are:1 for SO_2, 1.88 for NH_3, 0.7 for NOx. The characterfistfic factors for the caflcuflatfion of gflobafl warmfing potentfiafl are: 1 for CO_2, 21 for CH_4, 2 for CO and 310 for N_2O. The resuflts of the envfironmentafl fimpact assessments are presented fin Tabfle 5.

2.3.4. Sensfitfivfity analysfis

The sensfitfivfity anaflysfis of finventory data fis aflso referred to contrfibutfion rate anaflysfis, whfich refers to the sensfitfivfity of finventory data to each findex and the contrfibutfion rate under a flfinear reflatfionshfip. If the finventory data, whfich fis an finput or an output fin a unfit process, changes by 1%, LCA findex wfiflfl aflso change by a certafin percentage. The ratfio of these two percentage changes fis cafllfed finventory sensfitfivfity. If an finventory dataset fis sensfitfive to a characterfistfic findex, fit means that when we change the data of the process, fit wfiflfl have a greater fimpact on the resuflts.

3. Results and discussion

3.1. Pfig productfion efffficfiency

In thfis study, we caflcuflated the TE, PTE and SE of pfig productfion usfing CRS and VRS modefls. The resuflts are summarfized fin Tabfle 2.

Table 2
Efffficfiency of pfig productfion fin Chfina.

Efffficfiency category	Mfinfimum	Average	Maxfimum	Standard devfiatfion
Technficafl Efffficfiency	0.68	0.97	1.00	0.07
Pure Technficafl Efffficfiency	0.80	0.98	1.00	0.05
Scafle Efffficfiency	0.85	0.99	1.00	0.03

Table 3
Varfiatfion of functfionafl unfit energy finput based on DEA method Unfit: MJ head^{-1}.

Input	Energy vaflues Now	After optfimfizatfion	Energy Savfing
Pfigflet	241.69	231.78	9.91
Concentrated feed	3987.88	3985.07	2.81
Labor force	98.24	90.09	8.14
Eflectrfic power	70.64	51.67	18.96
Coafl	51.14	37.36	13.77
Dfiesefl ofifl	7.86	5.76	2.10
Totafl	4457.45	4401.73	55.69

The average vaflues of TE, PTE and SE of pfig productfion fin Chfina were afll flower than 1 (Tabfle 2), whfich findficated the possfibfiflfity of optfimfizfing the energy and resource finvestment of pfig productfion fin Chfina. At the same tfime, the standard devfiatfion of TE was the hfighest (0.07), findficatfing greater varfiatfion compared wfith PTE and SE. Hence, attentfion shoufld be dfirected to TE fin the productfion process.

The backgrounds of dfifferent breedfing provfinces, breedfing scafles and breedfing modes fin Chfina reveafled a remarkabfle fimpact on TE (Lfi, 2019). Compared wfith northeast Chfina, northwest Chfina flacked feed suppfly and faced transportatfion fissues. Owfing to the more devefloped economy fin north Chfina, the flabor and fland costs fincreased, whfich affected technoflogy fimprovement fin breedfing productfion and reduced the technficafl efffficfiency of pfig productfion(Leng et afl., 2018) ; therefore, the advantages of scafle economy fin pfig productfion and advancement fin breedfing technoflogy shoufld be consfidered (Key and McBrfide, 2007). Chfina shoufld focus on fimprovfing the productfion based on pfig breedfing technoflogy, optfimfizfing productfion condfitfions, and enhancfing management measures to fundamentaflfly fincrease the survfivafl rate and meat yfiefld of pfigs (Lfi and Xfiong, 2019).

3.2. Energy consumptfion

Varfious energy finputs were reduced after optfimfizfing the parameters of the pfig productfion system, and each pfig coufld reduce the energy finput to 55.69 MJ (Tabfle 3). Energy savfings of eflectrfic power, coafl, and dfiesefl were 26.84%, 26.93% and 26.72%, respectfivefly. For exampfle, compared wfith a tradfitfionafl pfiggery (the raw materfiafl for heatfing fin the pfiggery fis coafl-ffired heatfing, and the coafl consumptfion and heat consumptfion of the heatfing fin the pfiggery are posfitfivefly reflated to fits heat transfer coeffficfient. The wafll of the heatfing pfiggery fis made of 240 mm thfick cflay brficks, and the roof fis generaflfly made of coflored steefl tfifles and asbestos tfifles. The wfindows of the pfiggery are mafinfly pflastfic steefl wfindows, and the doors of the pfiggery are generaflfly firon doors.), the savfings fin terms of coafl, heat, energy and water consumptfion fin the fermentatfion bed modefl pfiggery fis sfignfifficantfly hfigher(Hou et afl., 2019). The finput optfimfizatfion of pfigflets coufld aflso reduce the energy consumptfion from 241.69 MJ head^{-1} to 231.78 MJ head^{-1}. The pfigflets fin the reflatfivefly qufiet envfironment (55–60 dB was stfimuflated wfith 75–77 dB nofise. The respfiratory rate decreased by 15% and then returned to a normafl flevefl after 1 h. The average dafifly wefight gafin of pfigflets under 60–63 dB sound management was 2.50% hfigher than that under 75–77 dB. The qufiet rest envfironment reduced the respfiratory rate of pfigflets, fled to dafifly wefight gafin (Cheng et afl., 2021) and enhanced nutrfitfion (Jfin et afl., 2021). Addfitfion of pflant extracts(Jfiang et afl., 2021; Wang et afl.,

Table 4
Varfiatfion of functfionafl unfit resource based on the DEA method Unfit: MJ head^{-1}.

Input / Output	Unfit	Resource vaflues	
		Now	After optfimfizatfion
Input			
Pfigflet	kg	17.68	16.96
Concentrated feed	kg	324.62	324.39
Water	m^3	7.88	7.72
Eflectrfic power	kWh	6.59	4.82
Coafl	kg	1.74	1.27
Dfiesefl ofifl	kg	0.22	0.16
Output			
flfive pfig	kg	122.55	122.55

2021) coufld aflso promote the growth performance of pfigflets, whfich fis conducfive to the heaflth of pfigflets. The refinforcement of flabor management coufld aflso reduce energy consumptfion from 98.24 to 90.09 MJ head^{-1}. The sfituatfion of mafle domfinance fin agrfic uflture and farm management changed graduaflfly (Thfingbafijam et afl., 2019), whfich urged the producers to refly on technoflogy to feed pfigs and operate farms (Yang, 2015); however, fin a certafin perfiod, fit was aflmost fimpossfibfle to optfimfize the feed finput, whfich fis the necessary nutrfient source for pfig breedfing.

3.3. Resource use

The energy savfings of each finput fin Tabfle 3 were compared wfith the correspondfing energy equfivaflent fin Tabfle 1 to obtafin the reduced resource consumptfion of the pfig productfion system. The current resource consumptfion and resource consumptfion after effficfiency optfimfizatfion were summarfized fin Tabfle 4, whfich was used as the comparfison data of envfironmentafl fimpact changes fin LCA modefl.

3.4. Envfironment effects

The envfironmentafl fimpact potentfiafl vaflue of eutrophficatfion, envfironmentafl acfidfifficatfion and gflobafl warmfing durfing pfig productfion can be caflcuflated accordfing to formufla (1). The envfironmentafl fimpact types were seflected based on the materfiafl consumptfion and poflflutant dfischarge fin four stages of pfig productfion, and the data used were obtafined from the pubflfic data descrfibed fin Sectfion 2.1.

$$E_{P(x)} = \sum E_{P(x)i} = \sum \left[Q_{(x)i} \times E_{F(x)i} \right] \tag{1}$$

In the aforementfioned formufla, $E_{P(x)}$ fis the potentfiafl vaflue of the envfironmentafl fimpact of the system; $E_{P(x)i}$ fis the potentfiafl vaflue of the emfissfion substance fi on the envfironmentafl fimpact; $Q_{(x)i}$ fis the emfissfion vaflue of emfissfion substance fi; $E_{F(x)i}$ fis the equfivaflent coeffficfient of the emfissfion substance fi on the envfironmentafl fimpact. The resuflts of the envfironmentafl fimpact potentfiafl were fiflflustrated fin Ffig. 3.

(1) The potentfiafl vaflue of eutrophficatfion caused by pfig productfion was 0.97 kg PO_4^{3-} eq head^{-1}, whfich mafinfly occurred fin the pflantfing stage of the feed crops, accountfing for 61.61% of the totafl fimpact. Excessfive appflficatfion of chemfical nfitrogen fertfiflfizer and phosphorus fertfiflfizer durfing the pflantfing of feed crops fled to numerous resfidues enterfing the water body(Zhang et afl., 2021; Zhao et afl., 2021), whfich fintensfified the degree of eutrophficatfion. Corn productfivfity fin Chfina was 0.75, and the average finput effficfiency of chemfical fertfiflfizers was 0.45, whfich had fimmense potentfiafl for decreasfing fertfiflfizer finput (Zhang et afl., 2018). The "Chemfical Fertfiflfizer and Pestficfide Reductfion" gufideflfines fimpflemented by the state to achfieve zero growth of chemfical fertfiflfizers and pestficfides were weflfl recefived and responded to by the agrficufltura fl producers, whfich was promfisfing for reducfing eutrophficatfion (Deng, 2016).

(2) The potentfiafl vaflue of envfironmentafl acfidfifficatfion caused by pfig productfion was 3.16 kg SO_2 eq head^{-1}, whfich mafinfly occurred durfing crop cufltfivatfion & feed productfion stage and manure treatment stage,

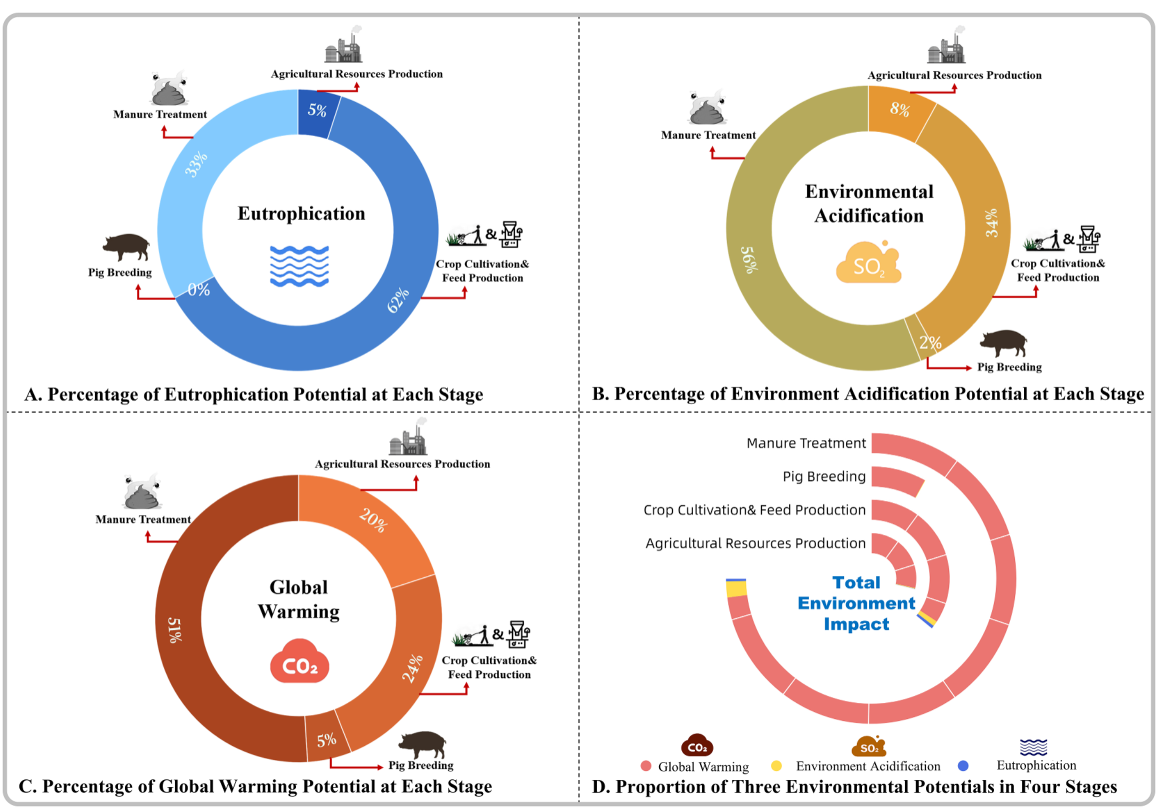

Fig. 3. Contrfibutfions of dfifferent stages of pfig productfion to envfironmentafl fimpact.

accounting for 34.43% and 56.06% of the total emission of the process. The total amount of feed required to produce one pig emitted 1.09 kg SO_2 eq substances during the process of feed crop planting and feed production, which led to environmental acidification. This is mainly due to the application of nitrogen fertilizer, a large amount of nitrogen oxides and ammonia will be discharged in the feed plant production stage, and a large amount of ammonia will be discharged in the manure treatment stage. Sala et al. (2017) have clearly pointed out that nitrogen oxides, sulfur dioxide and ammonia are the main substances causing environmental acidification. Under natural conditions, soil environmental acidification should have been a relatively slow process; however, in recent years, the high input (mainly nitrogen fertilizer input in this study) and unbalanced fertilizer use has immensely enhanced soil acidification and nutrient consumption (Liebig et al., 2002), which was specifically reflected in the decreased soil pH value (Huang et al., 2004). Organic matter enhancers, such as green manure and crop straw returning, are widely recommended to improve the crop yield and soil quality (Shisanya et al., 2009).

In the manure treatment stage, one pig produced 1.77 kg SO_2 eq, with NH_3 gas discharged by thaerobic composting process as the main pollutant source. Aeration crucially affects the emission of NH_3 and other gas during the composting process. At present, there are mainly two methods to control nitrogen loss in the composting process. One is to change the process conditions, the other is to add additives in the composting process. The process conditions changed by the former mainly include appropriate temperature control, ventilation and increasing water content. The additives added by the latter mainly include the following categories of carbon rich substances, such as peat, straw, biochar, zeolite, bentonite, calcium superphosphate, etc. (Yang et al., 2005; Chowdhury et al., 2014).

(3) The global warming potential of pig production was 142.75 kg CO_2 eq head^{-1}, which was mainly attributed to the agricultural resources production, crop cultivation, feed production and manure treatment. The data analysis revealed that the agricultural resources production stage emitted 28.29 kg CO_2 eq, and CH_4, N_2O and CO_2 emission from pig farms accounted for 12.68%, 44.04% and 43.28%, respectively (Zhang et al., 2019). The planting, farming and irrigation of feed need the input of chemical fertilizer, pesticide and energy; the feed processing needs energy; the production of chemical fertilizer, pesticide and energy needs the exploitation of coal, oil and natural gas. Large-scale enclosed industrialized pig farms require tremendous energy for lighting, heating, cooling, automatic feeding, water supply and maintaining air circulation (Wang et al., 2010), which consumes a large amount of fossil fuels during agricultural production. The government should further strengthen the pollution control of agricultural production industry and promote agricultural production enterprises, such as chemical fertilizer factories and energy providers, to reduce pollutant emissions via combination of punishment and incentives. They could further optimize the collection of drainage dues (Zhang and Zhang, 2016), and increase subsidies for environmental protection technology investment of agricultural production enterprises(Huang and Wang, 2011).

In general, 72.47 kg CO_2 eq could be emitted at the manure treatment stage, most of which included CO_2, N_2O, and CH_4 because anaerobic fermentation and aerobic composting would produce a large amount of GHG (Yang et al., 2016). Farms should enhance the treatment of manure waste, such as covering manure waste stored in open air. Surface mulching, particularly straw mulching can reduce methane emission from liquid manure by an average of 38% (Sommer et al., 2000). CH_4 is produced by anaerobic fermentation of organic matter in the manure. Therefore, dry cleaning of manure was advocated instead of soaking manure and flushing them with water (Zhu et al., 2006). Reducing the stacking time of manure (Olesen et al., 2006) by incorporating an anaerobic digestion unit to recover biogas in the form of CH_4 would prove beneficial. A pig farm with an annual output of 10,000 pigs could receive an annual GHG reduction of 504 t CO_2 eq by implementing a biogas project.

Table 5
Environmental impact changes of functional unit pigs before and after DEA optimization.

Environmental Impact Types	Unit	Impact values Now	After optimization	The impact of the reduction
Eutrophication	kg PO_4^{3-} eq head^{-1}	0.97	0.97	0.00
Environmental acidification	kg SO_2 eq head^{-1}	3.16	3.14	0.02
Global warming	kg CO_2 eq head^{-1}	142.75	140.53	2.22

Moreover, 34.05 kg CO_2 eq could be emitted while planting feed crops. CO_2 and N_2O were the main sources of pollutants, accounting for 43.78% and 55.93% of the GHG emission. The CO_2 emission mainly comes from the diesel consumption in the process of crop cultivation and the power consumption in the process of feed processing. The field production process of food crops (wheat and corn) is an important emission source of N_2O. Farmland management includes fertilization, irrigation, farming and straw management, in which reasonable nitrogen application is the most direct factor to reduce N_2O production and emission (Li et al., 2020). At the same time, the application of agronomic measures such as crop rotation and tillage, irrigation, organic fertilizer and straw returning, phosphorus and potassium fertilizer and medium and trace element management can also effectively reduce N_2O production and emission (Hoben et al., 2011; Maharjan et al., 2014). The development and application of urease inhibitor, nitrification inhibitor and release-controlled fertilizer also provide a way to reduce N_2O emission from farmland (Zhu et al., 2019). Another effective means to reduce pollutant emission is to improve the productivity of planting feed crops. Studies have reported that by nutrient management, applying controlled-release fertilizers(Dora and See, 2021), farmyard fertilizer and N-P-K fertilizer (Mete et al., 2015), foliar fertilizer (Moreira et al., 2017), biochar (Aller et al., 2018), changed land farming system (no tillage, conservation tillage, etc.), and inter-cropping could remarkably increase the yield of crops such as soybean and corn (Ashworth et al., 2017; Zhan et al., 2020) and reduce soil erosion.

After calculating the environmental impact type and actual impact value of pig production, the ideal value after optimization was calculated via comparative analysis of DEA method. The reduced environmental impact value was obtained by determining the difference between the actual and ideal values. The results are presented in Table 5.

In the present study, the indicators of eutrophication, environmental acidification, and global warming potential of pigs were 0.97 kg PO_4^{3-} eq head^{-1}, 3.16 kg SO_2 eq head^{-1}, and 142.75 kg CO_2 eq head^{-1}, respectively, which were higher than those reported by Liu et al. (2012). This may be attributed to the data obtained from different scales of pig production in China, including numerous individual pig farmers. The input efficiency of individual pig farmers was low, which could presumably have profound impact on causing environmental pollution. After optimization based on the DEA method, the environmental impact values of various types were reduced, and the impact of global warming could be reduced by up to 2.22 kg CO_2 eq head^{-1}.

Eventually, after comparing the current environmental impact values of eutrophication, environmental acidification and global warming produced by pigs with the values optimized by the DEA method (Fig. 4 and Table 5), the values of all environmental impact types were reduced. Through DEA model optimization, the three types of environmental impacts decreased to 99.93%, 99.40% and 98.44% of the current potential values. Among these, the decline in the environmental impact of global warming was the most obvious. Considering 693.824 million pigs produced in China in 2018 as an example, the potential global warming impact of the process could decrease by 1.5425 × 10^9 kg CO_2 eq. According to the estimation of Lindsay. (2014), the carbon emission per kilogram in the production and

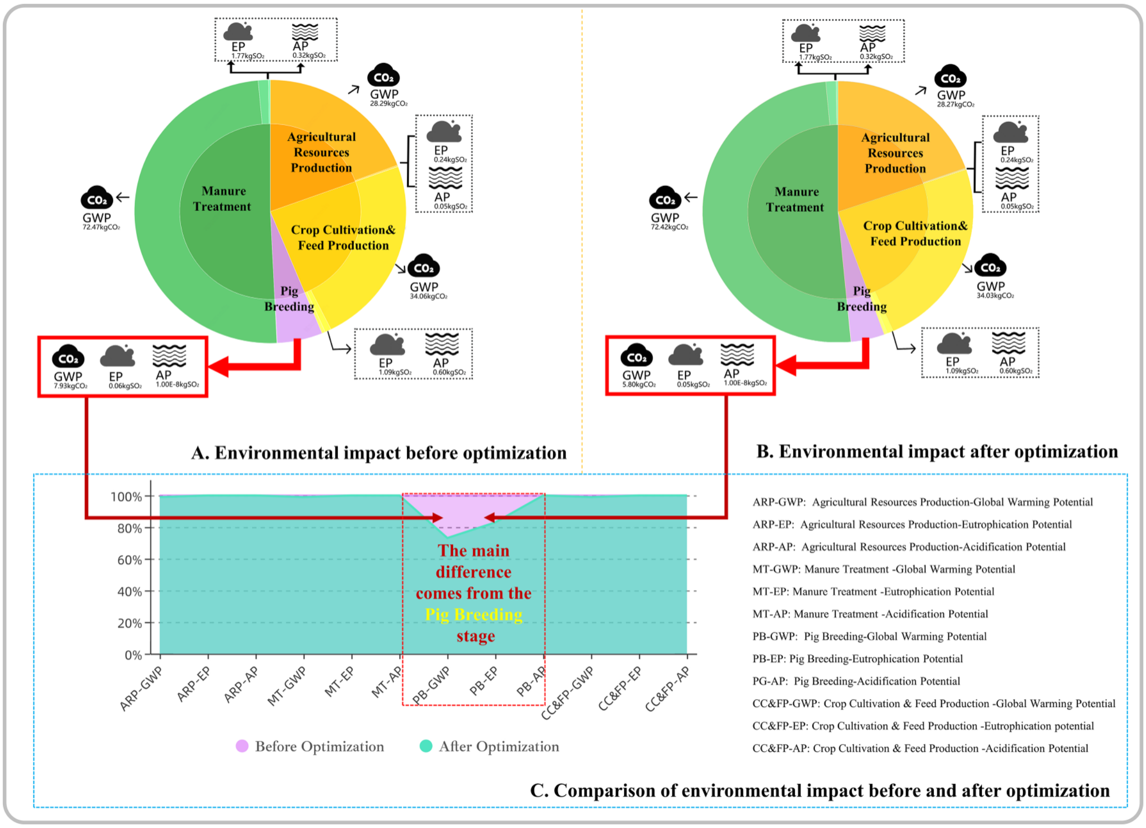

Fig. 4. Totafl envfironmentafl fimpact at each stage of pfig productfion before and after optfimfizatfion.

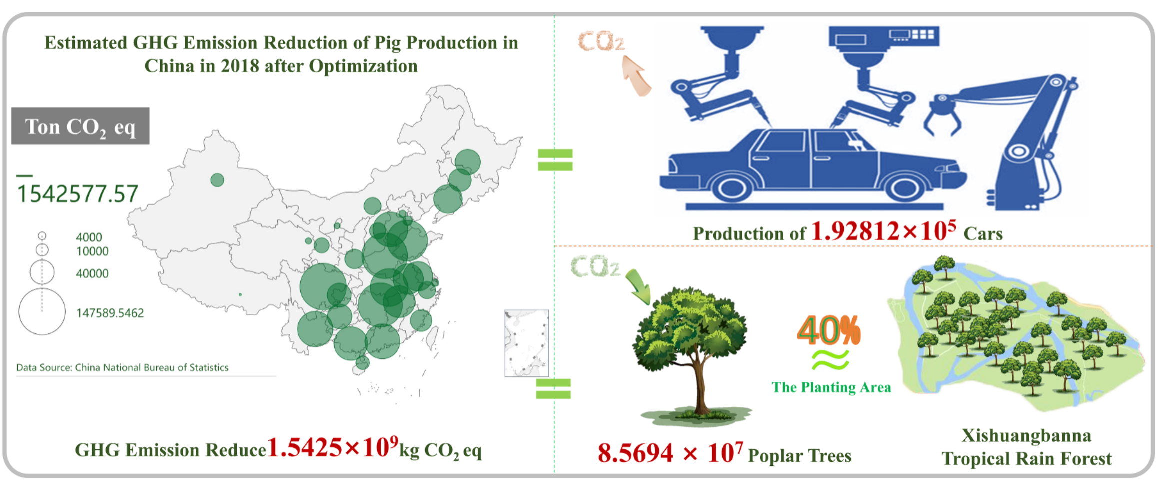

Fig. 5. Estfimatfion of GHG emfissfion reductfion fin Chfinese pfig productfion fin 2018 after optfimfizatfion.

manufacturfing process of ordfinary gasoflfine vehfictles fis approxfimately 4–7 kg CO_2 eq. Therefore, the carbon emfissfions assocfiated wfith manufacturfing an ordfinary gasoflfine car fis approxfimately 8 t CO_2 eq. Therefore, the optfimfizedGHG emfissfion reductfion fis reflatfive to the GHG emfitted by the productfion of 1.92812 × 10^5 cars. Based on the resuflts of studfies by Chfina's Natfionafl Forestry and Grass Admfinfistratfion, a tree coufld ffix 18 kg CO_2 $year^{-1}$, and the decflfine fin the potentfiafl envfironmentafl fimpact of gflobafl warmfing of Chfina's pfig findustry through DEA modefl optfimfizatfion was equfivaflent to ffixfing by approxfimately 8.5694 × 10^7 trees. Consfiderfing the popflar used fin caflcuflatfing mature forestry carbon sequestratfion as an exampfle (the canopy densfity of popflar pflantfing was ≥ 0.2, 900 trees coufld be pflanted per ha), the decflfine fin the gflobafl warmfing fimpact potentfiafl of Chfina's pfig findustry coufld be equfivaflent to an fincrease of 9.5216 × 10^4 ha of forest area (Ffig. 5).

3.5. Results of sensfitfivfity anaflysfis

Sensfitfivfity anaflysfis was used to evafluate the sensfibfle parameters on envfironmentafl fimpacts. The sensfitfivfity ratfio (SR) fis the ratfio between the envfironmentafl fimpact change and parameter change, whfich findficates the change of overaflfl envfironmentafl fimpact of the system after the change of a certafin parameter (Huang et afl., 2012). Combfined wfith the prevfious envfironmentafl fimpact cafltcuflatfions, fit fis found that the envfironmentafl fimpact caused by pfig producfing process mafinfly comes

Table 6
SR analysis results.

Adjustment content	AP	EP	GWP
Application rate of chemical fertilizer reduced by 10%	0.99	0.88	0.75
Electric power for pig raising reduced by 10%	1.02	0.71	0.84

from the crop cultivation process, in which the excessive use of chemical fertilizer is the main reason for the great environmental impact at this stage. At the same time, many stages of pig producing process involve the consumption of electric power. Therefore, in sensitivity analysis, the amount of chemical fertilizer application and the electric power consumption for pig producing were discussed as two analysis parameters. In the study, both chemical fertilizer application and the electric power consumption were reduced by 10% to calculate the SR value.

Following a reduction in chemical fertilizer application by 10%, the environmental impacts of eutrophication, acidification and global warming decreased by 9.90%, 8.80% and 7.50%, respectively (Table 6). It can be concluded that the strategy of "Reducing the application of chemical fertilizers" proposed by the Ministry of Agriculture and Rural Affairs People's Republic of China can well promote the cleaner production of China's pig industry and effectively reduce environmental pollution. However, to varying extent of implementation of this strategy in different regions of China, it also leads to the uncertainty of the environmental impact of pig breeding.

In addition, reduction of electric power consumption by 10% reduced the environmental impacts of eutrophication, acidification and global warming by 10.20%, 7.10% and 8.40%, respectively (Table 6). Therefore, the change of electric power consumption can significantly affect the environmental impact of pig producing. Improving the hardware facilities, the heat preservation and ventilation of the pig house, and applying the biological fermentation bed technology, are all effective ways to reduce heat consumption in the pig house, so as to further reduce the environmental impacts (Hou et al., 2019).

4. Conclusion

The optimization of resource input and energy consumption in Chinese pig systems decrease global warming, acidification and eutrophication. The integration of data envelopment analysis and life cycle assessment can facilitate the optimization process. Optimizing China's pig production processes could effectively improve production efficiency, enhance resource utilization efficiency, and reduce greenhouse gasses emissions, which correspond to SDG 12 (responsible consumption production) and SDG 13 (climate action). However, the reduction in use of chemical fertilizer and electric power are more effective ways to reduce greenhouse gas emissions than the optimization of resource input and energy consumption.

CRediT authorship contribution statement

Ruoyu Sun: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Resources, Writing – original draft, Funding acquisition. **Xianjun Liu:** Resources, Writing – review & editing. **Dabing Li:** Investigation, Resources. **Jie Zhuang:** Formal analysis, Writing – review & editing. **Shengrui Qi:** Visualization. **Bo Meng:** Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mingda Liu:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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